Articles from the Workshop on Remote Sensing in Agriculture in the 21st Century

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The following articles were received from participants at the remote sensing workshop. The text has been reproduced here to provide additional information and reference sources. Figures and illustrations have been omitted to save file space.

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TRW AG RESOURCE MAPPING: A COMMERCIAL AIRBORNE AGRICULTURAL REMOTE SENSING SYSTEM*

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Abstract

The TRW Ag Resource Mapping project has developed a GIS based, real-time, multi-sensor airborne environmental surveillance and mapping system for the remote sensing of agricultural crops. The system consists of two segments. The airborne segment uses a GIS based multi-sensor mapping workstation in a Beech Bonanza aircraft integrated to a GPS navigation system and a suite of five real time imaging sensors (six band multispectral, thermal infrared, video, color video, and computer controlled film cameras). All sensors are boresighted, displayed in real time, and snapshot images can be acquired from all sensors simultaneously during flight operations. Dynamic icons show aircraft location and real time sensor footprint. Imagery acquired is from 1-3 meter resolution (or better) and is precision georegistered to a digital map base. The ground segment consists of a GIS based customer request database, a mission operations management system (Apple Macintosh based), a flight planning tool, and a custom optimized imagery analysis and product generation system. The product generation system performs precision georegistration (1 pixel accuracy), data correction, normalization, and facilitates interpretation and generation of crop monitoring and diagnostic map products. The system flew for the 1994 growing season and a line of five remote sensing products were developed and provided to contracted customers.

Introduction

The idea of the use remote sensing techniques in agriculture has been around for many years. US Government programs have successfully used remotely sensed imagery to evaluate national and global grain crops for the past few decades. Despite these initial successes practical remote sensing has not penetrated the agricultural community to any significant degree.

As part of the ongoing TRW SIG interest in commercial applications of remote sensing, a nation wide market survey was performed to ascertain the degree to which existing agribusiness uses remote sensing technology and to find out how this could be

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[*] Presented at the Second International Airborne Remote sensing Conference and Exhibition, 24-27 June 1996. San Francisco, California, USA.

expanded in the future. The results indicated a minimal remote sensing presence in the agriculture business. Few aircraft based businesses have existed and none have had significant success. Most have utilized color infrared film (or a digital surrogate) and provide raw or minimally interpreted data output products. It has been seen that taking this approach has not allowed remote sensing firms to penetrate and / or significantly develop / expand the agricultural market for remote sensing data. Similarly, attempts to use satellite imagery have been made, but revisit times and inherent resolution restrictions have limited its usefulness and thusly its adoption. Specific care was taken to investigate both historical as well as currently existing remote sensing companies to compile a true evaluation of their practical successes and avoid biasing our subsequent evaluation of the market due to unfounded industry rumors and misleading marketing reports and publications.

Further evaluation of the competitive market indicated that previous attempts at developing viable agricultural remote sensing businesses have failed due to a number of key factors, including:

- poor understanding crop phenomenology and cropping methods
- poor understanding of major grower concerns and real economic problems
- poor understanding of remote sensing applications science
- lack of appropriate sensors
- lack of sophisticated systems integration capability (computer, software, aircraft)
- lack of practical air survey knowledge expertise
- incorrect and / or overestimation of the true achievable market (short term, long term)
- lack of a viable product distribution plan
- lack of cooperative product development research
- slow timelines in processing to final deliverable product

In response, TRW has developed an integrated multi-sensor airborne remote sensing system that addresses the critical problems and requirements of the agricultural remote sensing business. The light aircraft based system utilizes an airborne mapping workstation that controls video, photo, multi-spectral and thermal infrared sensors to rapidly acquire precision georegistered digital imagery data sets. A custom developed Geographic Information System (GIS) based ground workstation system allows for rapid acquisition and interpretation of imagery into one of five initial (Phase I) deliverable information products. An integrated product and customer business management system facilitated the processing of orders and delivery of the output data from the analysis production line.

The system was flown in 1994 in cooperation with commercial growers and agricultural cooperatives. Crop types that were imaged included potatoes, corn, mint, sugar beets, alfalfa, and various orchard crops. Useful hard copy information products were interpreted and provided to growers under contract within 24 - 48 hours. Information products that were produced addressed irrigation management, crop health, crop change detection, fertilization, soil mapping and harvest yield applications. The system flew nearly every day for the entire growing season covering fields within 1()0+ mile radius of the base facility. In tests the system demonstrated the capability to survey approximately 720 contiguous quarter section fields (l meter resolution) in a five hour flight period (9:30 AM - 2:30 PM.) equaling a ground area of over 92,000 acres. The program demonstrated that integrated airborne remote sensing systems can acquire, process, interpret and deliver timely (weekly, bi-weekly, daily) multi-sensor, multi-spectral, high resolution (1 meter - 1 ft.) data over large enough areas to support practical agricultural surveillance applications. The sensor systems demonstrated that commercially useful agricultural information products can be derived from low to moderate cost sensors available today. The ground processing capability demonstrated that, using custom developed software, large volumes of imagery data can be processed and interpreted in the timelines require to support 24-48 hr customer requirements.

The general system, concepts, and processes for both airborne and satellite applications are covered in U. S. Patent No.5,467,271 "Mapping and Analysis System for Precision Farming Applications".

System Description

Operational Requirements Analysis

The functional requirements for the system were derived from direct and lengthy discussions with agricultural consultants, field men, agricultural co-op staff, growers, experienced agricultural remote sensing professionals, image processing experts, air survey pilots, agribusiness managers, and computer systems design engineers. In addition, the systems, products, business practices, and market approach of previous agricultural remote sensing companies, were analyzed in order to learn from both their areas of success and failure. From this, the initial set of requirements was modified to define a requirements document for an optimal integrated agricultural reconnaissance system (remote sensing, sales management, and product generation). These inputs were used in developing the guiding functional requirements for the system development. A subset of the more significant operational requirements is as follows:

- Fly and survey fields up to 100+ miles from the base airfield.
- Maximum survey of 90,000 acres a day (multispectral) 130,000 acres (other)
- Process 100 completed output products per analysis shift
- 48 hr (maximum) product delivery from "wheels down" to customer door
- Multi-sensor (photo, multispectral, thermal infrared, video)
- Full digital map based real time system
- Precision georegistration of imagery to facilitate 1 meter target location accuracy
- Fully interpreted output product (no raw data provided, full service company)
- Database archive for all imagery (to facilitate change detection / temporal analysis)
- Develop specific crop diagnostic tools targeted at specific high value problems
- Mission planning capability

- Integrated PC based business management tool set
- All acquired sensor data must be recorded for later replay and review.
- Latitude and longitude coordinates for all imagery, fields center, and annotation locations shall be available for display and/or annotation by the airborne operator.
- Ideally the system should be a low-cost implementation of all of the above factors.

A systems requirements document was developed from these guidelines and a system prototype design developed in 1992-3. A prototype system was flown late in the growing season in 1993. This system mapped late harvest potato and alfalfa crops in an integration and testing phase.

General System Description

The system consists of two main segments, the airborne segment and the ground segment.

The airborne segment uses a single engine Beech "Bonanza" aircraft as the imaging platform. This was selected due to its availability, climb rate, and speed (lower transit times, broader coverage). The workstation system was mounted in the copilot seat position facing rearward such that the system operator sat in the rear seat for operations. All sensors were mounted to look downward (nadir looking). The multispectral and photo sensors looked through ports in the fuselage. The thermal imager was located on a removable rack that extended from the right side door. The aircraft was equipped with all standard air traffic control voice communications equipment as well as an intercom. The aircraft position, altitude and attitude information was provided by an onboard 3-D GPS system (Ashtech, Trimble). The airborne workstation rack housed a Sun Sparc computer with associated peripherals (display, keyboard, trackball, disks, etc.)

The ground segment performed both data analysis as well as business administration functions. The business administration functions utilized an Apple Macintosh based business management and customer database software package. This software was developed to record and track customer requests for service, to provide daily target lists for mission planning, and to follow-up with billing once data delivery was confirmed. This system and was connected to the Sun analysis groundstation via a local area network. The Sun Sparc based analysis workstations were used to enter, process, rectify, and georegister, and interpret the acquired remote sensing imagery. There were four workstations in the ground segment, one for photo image input (scanning station), one for data quality assessment and georegistration, one for interpretation and product generation, and one for product quality assurance and hard copy output. All workstations were reconfigurable to perform any of the required functions as workload demanded. The analysis software for the ground and airborne workstations was custom developed in order to meet the processing rates and response times required by a successful system. (Note that various commercial image processing packages were evaluated for utility and none could meet the throughput requirements for a high output system) Both the business and analysis systems worked in concert to manage and monitor the progress of the data from customer request to delivery.

Functional Data Flow in the Commercial System

Contracts for remote sensing services were set up in the pre-season and included many regularly scheduled overflights. These requests (orders) were entered into the business database. The request data included what products were desired as well as the location of the field(s) to be imaged. Ad-hoc or custom requests were similarly entered into this database. Each day the list of orders for that day were generated by the business system and an output list of targets with their locations was passed to the mission planning portion of the analysis system. An interactive tool was used to plot these on the digital map. The pilot and aircrew then generated an optimal flight pattern to address these targets. This target list and flight plan were then downloaded to the computer on the aircraft via a local area network connection.

Once airborne, the aircraft would overfly each of the target fields and the workstation operator would capture video, thermal and multispectral freeze frames for each field. Aircraft navigation and sensor data capture was facilitated by two sets of monitors (one for the operator, one for the pilot) showing the digital map with dynamic (live) aircraft and sensor footprint icon, as well as the live video outputs from the sensors. As each image is captured the system records the position, altitude, and aircraft attitude required to register the image to the map (model based registration) and displays a graphic sensor footprint outline (static) on the digital map for reference. As each set of digital data is acquired the system also actuated the film camera, resulting in a 5 sensor boresighted image data set being recorded for each customer field. This process was repeated until all targets were imaged. Once the mission is completed the operator then dumps the digital data to 8 mm digital tape.

After landing the operator takes the 8 mm tape to the ground analysis segment and the film to the processor. The 8 mm digital tape is read into the system producing multi-sensor image data sets for each field. The film is processed within 1 hour and the negatives and / or hard copy prints brought back to the analysis center. The photo data is scanned in (negatives or hard copy prints) using a tabletop scanner and associated with the appropriate digital data sets. The completed data sets are then entered into the processing cue associated by customer name and field identifier. The processing cue keeps track of what has been done to each data set. As each image completes a step in the analysis workflow, the cue monitor will forward it to next cue for further processing. In this way all data is tracked in the system. At any time the operators can check the cue for the status of any field product.

Processing Step 1: Raw Data Quality Assessment

This function of this first processing step is to review the data for integrity and prevent inappropriate data from entering the processing flow. The Raw Data QA operator selects data for a customer field from the processing cue and reviews the data for problems (clouds, poor illumination, misalignment, poor resolution, data corruption, etc.). Any data sets found unacceptable are discarded and a request put into the business database for another imaging mission. Passed imagery are sent to the Georegistration processing cue.

Processing Step 2: Georegistration - Model Based and Precision CCP Georegistration

This step performs the georegistration of the imagery to the map, and the coregistration of one image to another. To start, the operator selects a field to review from the processing cue. An initial digital image (usually a photo) is displayed and georegistered to a digital basemap using either a model based georegistration process (low accuracy) and/or a precision conjugate control point (CCP) process (high accuracy). Precision registered maps and imagery are used as references for the CCP georegistration processes. The operator checks the registration accuracy by comparing images with interactive tools. Once satisfied with the registration accuracy, the operator repeats the process for the other digital data sets ending with a precision georegistered (and coregistered) multi-sensor image data set for the customer field. The finished data sets are entered into the Analysis and Interpretation cue. Any data sets that cannot be registered acceptably are discarded and a request put into the business database for another imaging mission.

Processing Step 3: Interpretation and Output Product Generation

This step is where the actual interpretation and analysis of the image data sets is performed. The operator selects a field for interpretation from the Interpretation and Analysis cue. Depending on the product that is requested, a custom product generation window and tool set will display on the screen. The interpretation and annotation of the data is completely interactive. The operator then reviews the imagery data sets as required, and interprets the data appropriately. Among the functions available to the analyst are magnification, normalization, enhancement, pseudocolor, and a set of proprietary task specific image processing and analysis algorithms. The imagery is processed and interpreted, and the analyst annotates notes directly onto the imagery as well as in text fields in the interactive report forms. A different analysis/diagnosis is performed for each output product, crop, region, and customer, etc. and different output products/maps are produced for each application. Once completed the operator enters the finished interpreted output product into the Product Quality Assurance Review, Output, and Delivery cue. Any data sets that cannot be interpreted appropriately are discarded and a request put into the business database for another imaging mission.

Processing Step 4: Product Quality Assurance Review, Output, and Delivery

This step performs the final quality check of the data and authorizes delivery of the data. The operator selects a field for interpretation from the Output cue and reviews the interpretation performed by the analyst. If all is well, the operator send the output product to the color printer for printing. When the output has printed it is then delivered to the customer that day or early the next day. The system automatically updates the business management software that this product has been delivered and the business system generates the billing request.

Data Capture

The airborne workstation continuously displays the real-time video imagery from all on-board sensors as well as recording it, along with navigation data, onto on-board VCRs. During flight, the airborne operator has the capability to capture freeze-frame imagery from the real-time sensor video feeds at any time simply by pressing a button. These digital freeze frames are stored on the system hard disks. Since both the video frame and the navigation and attitude data are captured simultaneously, the imagery can be georeferenced (warped) to a digital map base using a geometric projection model. The VHS tapes of each mission (having both navigation and video data on them) can be used to replay the entire video portions of the mission later when on the ground. All freeze frame functions are available during replay as well.

Sensors

A sensor survey was conducted in order to define a sensor or sensor suite that would be best for agricultural applications. Photo was selected because it is the most widely used and contains the most information per image (resolution, etc.). It is familiar, known, and the most powerful remote sensing tool to date. Multispectral (MS) was selected because of its uses in vegetation analysis, particularly in the areas of previsual stress detection. A 6 band video MS system was used in this application with growth plans to move to a more capable system (multispectral/hyperspectral scanners or FPA’s cameras) if the applications and market warranted. The bands selected were generally in the red, green and near infrared portions of the spectrum. Thermal infrared was added for research into irrigation and plant stress applications of these wavelengths. Color video provides a natural color scene context for the comparison of the data sets.

Navigation System

The aircraft was equipped with a Trimble Vector and later an Ashtech 3-D navigation system providing latitude and longitude position, and altitude as well as aircraft pitch, roll and yaw directly to the workstation. The initial system used CA code GPS, but was later fitted with a differential system to increase accuracy.

Airborne Mapping Workstation

A digital map-based airborne workstation was developed to provide sensor control, data capture, data recording, and image georegistration capabilities. The system was based on a Sun Sparc 10 computer running UNIX and Motif.

The sensor units all provided RS-170 video output to the workstation. The navigation and sensor system data were fed into the computer in real-time and used to generate a dynamic aircraft position and sensor footprint icons that were displayed over a digital map. These real-time moving icons were used by the pilot and operator to guide the aircraft over the target fields. The system provided full display capabilities for both raster and vector background base maps. Agricultural irrigation and ownership maps were scanned and entered into the system for use as the primary map base. Several different maps of differing scales can be stored and used by the system as appropriate. This allows for operation at different altitudes, and for navigation over both small and large areas. The maps and the dynamic icons were especially useful in locating fields in areas where the field pattern was very regular, roads were similar, and all the crops were the same. The system provides full map pan, roam, and zoom capabilities. The real-time sensor video information is displayed on either the workstation screen or auxiliary monitors. The operator has a tool set to allow the freeze-frame capture of the imagery from the real-time data stream. Captured images were written to disk with all required information ephemeris to properly georegister them to the map. Captured images can be warped and displayed directly on the digital map. Image mosaics are generated from successive freeze-frames. A frame capture intervalometer function facilitated continuous "hands off" aerial survey type mapping. The workstation also provides the operator with an interactive enhancement and annotation tool set for the interpretation and marking of generated maps / mosaics.

Geometric Pointing Models & Data Capture

Proper and accurate image georegistration requires a fully parameterized image warping projection model. This model must take into account all of the geometric parameters affecting the projection of the image onto a 3-D surface. Among these are aircraft position and altitude, sensor pointing in relation to aircraft reference axis, the optical model for the specific sensor itself, and the 3-D elevation characteristics of the terrain that is imaged. All of these parameters are modeled and / or acquired continuously in real-time to allow the system to correctly project and warp the imagery to provide accurate geolocation of the entire image. Precision georegistration was achieved by a conjugate control point warping process using reference imagery as the basemap.

Data Recording, Archive And Mission Playback

All mission imagery and navigation data is recorded to video tape onboard the aircraft. This allows the user to replay the video back to the ground workstation for post mission analysis and have the aircraft position icon and sensor footprint dynamically displayed in concert with the video imagery. From this full functional replay capability, the user can capture image frames and generate new image mosaics at the groundstation as needed. All enhancement and annotation capabilities are also available during replay.

System Integration

Aircraft Modifications

Aircraft modifications required for the mapping workstation system consisted of the addition of an external GPS antenna suite, installation of the workstation rack on the copilot seat position, installing the sensor and CPU payloads in the rear luggage area of the plane, mounting the thermal sensor OD the door mounted support arm, and the installation of a mole powerful alternator to provide the required DC power.

Workstation Integration

The front workstation rack (position on the copilot seat rails) held the Sun Sparc display, the keyboard and trackball, and the auxiliary sensor displays only. The rear airborne mapping workstation rack held the Sun Sparc 10 CPU with internal disk and tape drives, the GPS unit, the Multispectral system, the color and B&W video electronics, the Thermal system electronics, a power conditioner, a hard copy map storage pocket, and a fire extinguisher.

The main workstation power breakout switch with fuses and cutoff switches was located on the front of the rear workstation rack. In addition, a main fuse box was mounted in the cockpit to provide for pilot master control of aircraft power. This is an important safety precaution that allows the pilot to turn the power off to all system if needed in an emergency.

One goal of the design was to produce a system that would require minimal aircraft modifications and would allow the aircraft to be easily and quickly converted from surveillance mode back to a passenger or cargo mode. This resulted in the system being integrated as a nominally carry-on, carry-off package. The rack mounted airborne workstation system could be installed or de-installed in about one hour.

Due to the sun glare that can be encountered in flight, the windows of the aircraft had removable shades to allow the operator to darken the cabin for workstation operations.

Flight Testing & Demonstration: Washington State Operations

In 1994 the operational system was deployed to the Columbia Basin region of Washington state, a region well known for high value potato production. Contacts for the overflight of multiple crops for multiple customers were developed. Early in the season operational demonstration flights were conducted to test and demonstrate the functionality of the remote sensing system as a whole. Flights were made over target fields to verify the sensor boresight and the projection models.

The system was flown in support of customer contracts during the 1994 growing season beginning in March and ending in October. Usually two flights were scheduled per day to bracket the solar zenith. For products that were not effected by the illumination characteristics (irrigation monitoring) the aircraft could fly all day long, given pilot availability.

Results

The system flew nearly two flights daily (weekdays) for the entire growing season in 1994 (weather restricted many flight opportunities). Five basic remote sensing based agricultural data products were developed, implemented and delivered to customers. These included pre-season field analysis as well as late season crop monitoring products. The onboard sensor and processing systems performed reliably during the entire period. The ground station processed a maximum of over 100 output products a day (one processing shift) during peak requirements. Both air and ground station operators were trained in the use of the system within 2 weeks of initial exposure. The business management system successfully handled and tracked the requests and deliveries of all products.

The data products provided by the TRW remote sensing system assisted the growers in monitoring their irrigation and crop management practices. In many cases, the crop monitoring data provided valuable information about the status of the crop that was unknown to the growers using their traditional practices. TRW remote sensing interpretations were combined with crop consultant services to provide the complete problem detection and solution provision to the contracted growers.

Conclusions

The ACCUSAN system shows that light aircraft systems can address the spatial resolution, spectral resolution, temporal resolution, coverage and product delivery timeline requirements needed for commercial agricultural remote sensing applications. Specifically it has shown that:

- Light aircraft have the stability and flight performance that can be successfully used in agricultural remote sensing.
- Standard commercial off the shelf (COTS) hardware (computer and navigation) can be used with confidence in the light aircraft environment with minimal system failure rates.
- On-board digital imaging and mapping systems facilitate the acquisition and precision georeferencing of acquired imagery.
- Image processing techniques can be used effectively to define agricultural information from remote sensing data sets
- Spatially accurate maps of vegetation and soil characteristics can be generated using an integrated system
- System operators initially experienced in the use of PC computers can quickly and effectively be trained (3-4 days) in the complete hands off use and operation of UNIX-based Sun computers in both airborne and ground station applications.
- Custom processing software and man machine interfaces (MMI's) designed for the tasks of a specific application can optimize the effectiveness of the system in real world performance (versus concatenated general purpose IP and georegistration packages).

TRW AG RESOURCE MAPPING:
AGRICULTURAL REMOTE SENSING PHENOMENOLOGY*

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Abstract

The TRW Ag Resources Mapping Program conducted a series of ground truth-based agricultural remote sensing experiments to identify spectral signatures that might be used to remotely detect and classify vegetative stress characteristics. A season's worth of hyperspectral measurements were taken in a set of 18 test plots. Each test plot contained Russet Burbank potatoes cultivated under distinct water and nutrient stress levels. Spectral readings (from 450 to 2400 nanometers) were taken of each of the test plots to identify spectral regions and specific spectral wavelengths of reflected light that might be indicative of specific types of nutrient stress. The results of these tests show that the greater the nitrogen deficit, the further the spectral response was reduced in the near IR and SWIR (shortwave infrared) spectral. Spectral signatures from the test plots containing potassium, phosphorus, or water deficits all show similar reflectance depressions in the near IR and SWIR range.

The Need

Farmers and growers are continually looking for ways to improve their crop yields. They must balance limited use of fertilizer, pesticide and irrigation with a desire to produce high quality output. Often it is hard for growers to detect potential problems with crop yield until it is too late to respond effectively. In addition, the increasing size and productivity of agricultural operations is forcing a requirement for increased environmental sensitivity. Precision farming equipment, such as precision irrigation systems and precision spreaders, provide the application controls needed to lead the world into environmentally safer agriculture. What is lacking are more comprehensive and nondestructive methods for obtaining the data needed to prescribe variable treatments.

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* Presented at the Second International Airborne Remote Sensing Conference and Exhibition, San Francisco, California, 24-27 June 1996.

Well-known relationships between simple- spectral ratios, such as the normalized difference vegetative index (NDVI) and the existence of crop stress have been validated (Jackson, 1984) (Curran, 1989) (Plummer, 1988). However, the information provided by these indices has been extremely limited primarily for one reason: There is a many-to-one relationship between the possible causes of vegetative stress and the resulting stress signature. Therefore, the farmer does not know what problem they have and what to do about it. A quantitative prescription cannot be readily derived from the available data.

At present, identifying the cause of vegetative stress and determining the appropriate treatment levels are generally limited to soil and tissue sampling. This sampling is typically performed by spot sampling one or a few areas in a field or by taking many samples on a 100- to 200-foot grid across a field (grid sampling). These field sampling approaches and subsequent data analyses are localized, labor intensive, and costly to perform. In the case of gridded sampling, they are also destructive to the soil.

Goals

We conducted a series of test during the 1994 growing season to quantify potato canopy spectral signatures associated with specific types of nutrient and water stress. The goal of our experiment was identify distinctive spectral signatures associated with nitrogen (N), potassium (K), phosphorus (P) deficiencies and / or water stress. These nutrients were chosen due to the important and well-established relationship they have on crop development. Nitrogen application can be varied via the sprinkler system. Phosphorus and potassium are typically the major subject of pre-season fertilizer spreading to prepare the soil. Water stress was examined with regards to the varying patterns created by a periodic delivery system such as a center pivot and how to fine tune that delivery to eliminate water stress and over watering.

Our tests focused on Russet Burbank potatoes in Washington’s Columbia Basin. The ultimate goal of these experiments was to identify parameters that could be used in an airborne monitoring program to assist potato growers in better regulating nutrient treatment and irrigation rates. Two distinct sets of experiments were performed: nutrient monitoring and water stress monitoring. This paper discusses the results of the nutrient monitoring experiment.

Approach

A season’s worth of ground measurements were taken in a set of 18 test plots. Each 17 x 28 meter test plot contained Russet Burbank potatoes cultivated under distinct water and nutrient stress levels. Figure 1 shows the experimental layout of the test plots. These plots received 80, 100 and 120 per cent of a “normal” evapotranspiration irrigation rate and varying nutrient treatments of nitrogen, potassium and phosphorus. Six test plots contained 40, 60, 80, 100, 120 and 140 percent of the normal recommended nitrogen treatment at a 100 percent evapotranspiration irrigation rate. Six test plots contained 80, 100 and 120 percent of the normal recommended nitrogen treatment at a 80 percent or a 120 percent evapotranspiration irrigation rate. Three test plots contained normal, subnormal and above normal phosphorous treatments at a 100 percent evapotranspiration irrigation rate. The soil in the test plots was Shano silt loam.

The potato experiments were conducted near Othello, Washington. Daily maintenance on the plots was performed by Washington State University (WSU) personnel. Irrigation regimes were controlled with a linear system that was adjusted to provide different water treatments on individual test plots. Other sensors present in each of the test plots included air temperature probes, relative humidity sensors, rain gauges and soil moisture probes. Soil and petiole samples were taken in each of the 18 test plots each week for lab testing. Neutron probe soil moisture readings, one per test plot, were done weekly at the Othello test site by the same technician performing the spectral readings.

Spectral readings (from 450 to 2,400 nanometers) were collected of each of the 18 test plots on a weekly basis throughout the growing season using an Advanced Spectral Devices FieldSpec-FR Spectrometer. Five spectral measurements were made weekly in each of the 18 test fields from a height of 4 meters. Given the 25 degree field-of-view of the FieldSpec sensor, readings from a height of 4 meters resulted in a measurement footprint diameter of about 2 meters. Care was taken to collect all spectral measurements close to midday with a consistent orientation relative to the sun. These spectral samples were then processed and analyzed to identify spectral regions and specific spectral wavelengths of reflected light that might be used to remotely and nondestructively determine nitrogen, potassium and phosphorus treatment levels across a field.

Results

Analysis of the experiment data focused on the correlation of the type and degree of nutrient and water stress with the canopy's spectral signature. Figure 2 compares the spectral response of three test plots which received 40, 60, and 100 percent of a normal nitrogen fertilizer treatment throughout the season. These plots represent an average of 80 spectral samples, i.e. most of the spectral readings collected throughout the growing season for these specific test plots.

The most obvious outcome of the analysis was that the greater the nitrogen deficit, the further the spectral response was reduced in the near IR and SWIR (shortwave infrared) spectral ranges—i.e., from about 750 through 2,400 nanometers. In particular, the amount of reflectance in the near IR dropped from about 95 percent for the healthy test plots to about 75 percent reflectance for the 40 percent nitrogen deficit plot, and 6S percent reflectance for the 60 percent nitrogen deficit plot. This outcome is not surprising in the near IR range, and is the basis for most current vegetation monitoring indices. However, little crop stress monitoring work had previously been done in the SWIR and it had not been certain until now whether this depressed spectral response pattern would be consistent throughout the SWIR.

Previous research (Boochs, 1990) has indicated that for some types of vegetation the shape of the spectral signature's first differential in the vicinity of the red edge (i.e., between 670 and 770 nanometers) can be useful in distinguishing between different types of vegetative stress. Red edge first differentials were generated and evaluated for each of the nutrient and water stress data sets.. Although the magnitude of the peak decreases due to the depressed near IR spectral response of the stressed potato plots, no definitive red edge spectral shifts are apparent in the data.

While the reduction in near IR and SWIR reflectance values is promising as a gauge for estimating nitrogen deficits where all other sources of stress are already quantified, this situation is rarely the case. Analysis of the spectral signatures from the test plots containing potassium, phosphorus, or water deficits all showed similar reflectance depressions in the near IR and SWIR range. The only exception to this pattern were some subtle variations in the reflectance ratio of the green, red, and near IR bands which may or may not be statistically significant. The bottom line is that for now hyperspectral measurements spanning the 450 to 2,400 nanometer range can quantify the relative degree of stress in potato fields, but cannot with certainty distinguish between stress signatures of nitrogen, phosphorus, potassium, and water deficits

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THE SPACE-BASED HYPERSPECTRAL IMAGER AND APPLICATIONS DEMONSTRATIONS

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Abstract

TRW will launch a hyperspectral imager aboard its NASA-sponsored Lewis spacecraft in 1996 to support new application demonstrations and enhanced earth observations. The TRW-developed HSI covers spectral ranges from 0.4 to 2.5 micrometers with a ground sample distance of 30 meters. The satellite will focus on a series of technology and imaging demonstrations. TRW's science and commercial teammates will be studying applications in agriculture, forestry, environment and others. This paper describes the instrument capabilities and presents an overview of the applications development.

Introduction

The benefits of spectral imaging have been addressed in university research for more than a decade(1-5). Several airborne instruments have been available for applications development and studies; in addition, new airborne instruments with refined capabilities have been recently flown or are nearing completion(6-9). The use of airborne instruments is a natural way to develop algorithms and techniques. Typically, the image resolution is determined by instrument design and aircraft altitude and this can be varied to understand resolution impacts on phenomenological processes. In addition, aircraft systems allow opportunistic collections because of their scheduling flexibility with respect to weather. Satellite systems, on the other hand, permit broader, recurring views to address larger scale and regional issues. Until now, there have been no space-based hyperspectral instruments to provide this option. The TRW Lewis satellite, with two hyperspectral imagers, will be the first satellite to support hyperspectral imaging (see Figure 1). Both sensors, the TRW hyperspectral imager (HSI) and the NASA Goddard linear etalon imaging spectral array (LEISA), provide approximately 5 nm spectral resolution and spatial resolutions of either 30 or 300m (see Figure 2 and Table 1). To evaluate the impact of these new space-based remote sensing capabilities, TRW has assembled a university and commercial team to investigate and validate applications of hyperspectral imaging. This team is focused on extending current research and development in areas such as agriculture, forestry and environment. A description of both the instruments and selected application areas is presented in this paper.

Table 1. SSTI Lewis Payload Characteristics

Mission Parameter	HSI	LEISA	UCB
Operational Design Life	5 years	1 year	3 years
Global Access/Revisit Period	7 days	3 days	N/A
Ground Sample Distance (GSD)	5m pan	-	N/A
	30m HSI	300 m	N/A
Scene Local Time (nominal)	10:30-11:00 am	10:30-11:00 am	N/A
Swath Width			N/A
	12 km pan	-	N/A
Swath Length ("Scene" Definition)	7.7 km HSI	77 km	N/A
Band Selectivity	20 km	250 km	No
Abs. Grnd Sample Position Knowledge	Yes	No	<0.5 deg
	<200 m (3σ)	200 m	side-real
Minimum Daily Mission Data Volume			pointing
Longest Continuous Data Acquisition	1 Gbit	1 Gbit	1 Gbit
Period	2 min	10 min	30 min
Minimum Functional Data Acquisition			
Frequency	Once/orbit	Once/orbit	Once/orbit
Minimum Data Acquisition Period			
Required	3 sec	30 sec	15 min
Satisfy Performance Requirements			
Data Latency (to Stennis Data Center)	< 24 hours	<24 hours	~ week
Spectral Range	0.48 - 0.75 µm pan 0.4 - 2.5 µm HSI	1.0 - 2.5 µm	55-105 nm
Spectral Resolution	6 nm VNIR SWIR	1/250	0.5 nm
Bit Resolution	8 bits pan	12 bit	N/A
	12 bits HSI		
Radiometric Accuracy (Absolute, I-s)	<16% pan	-	N/A
	<6% HSI	10%	
Pixel to Pixel Precision (Relative, I-s)	<4%	-	N/A
	<2%	<4%	

Airborne and Spaceborne Hyperspectral Instruments

TRW Hyperspectral Systems

TRW has been flying hyperspectral instruments since 1990. A summary of the instruments, including the ones under development is given in Table 2.

Table 2. Performance Comparison of TRW's Family and HSI

	TRWIS B	TRWIS II	TRWIS IV	TRWIS III	SSTI HSI
Spectral Range (microns)	0.46-0.88	1.5-2.5	0.45-0.88	0.4-2.5	0.4-2.5
Spectral Channels	90	108	230	384	384
Spectral Sampling (nm)	4.8	12	1.8	5VNIR 6.25 SWIR	5VNIR 6.38 SWIR
Spatial Pixels	240	240	240	256	256
IFOV (mrad)	1.0	0.5/1.0	0.5/1.0	0.9	0.06
TFOV (mrad)	240	120/240	120/240	230	15.4
Aperture (nm)	5	17.5/8.5	25.12	20	125
Focal Length (mm)	25	70/34	50/25	70	1048
Focal Ratio	f/5	f/5	f/2	f/3.3	f/8.3
Detectors	SiCCD	InSb	SiCCD	CCD/HCT	CCD/HCT
Quantization (bits)	8	8	8	12	12
Recording Media	videotape	videotape	videotape	digital	digital
Year	1991	1992	1996	1996	1996

The TRW Imaging Spectrometer (TRWIS) B was developed from commercially available components and has served as a testbed and applications demonstrator(see Figure 3). This instrument covers the visible and near IR spectrum with 4.8 nm spectral sampling. It is compact and lightweight and has adapted easily to various aircraft platforms from an ultralight to a Lear Jet. TRWIS II was developed to measure the SWIR from 1.5 to 2.5 microns with 12 nm channel width. It uses a custom IR lens, a SPEX 270M spectrometer (repackaged) and a modified InSb camera. TRWIS IV is an upgrade of TRWIS B.

This system is undergoing flight test and performance validation at the present time. The latest generation of TRWIS hyperspectral instruments, TRWIS III(10) shown in Figure 4, provides broader spectral coverage (0.4 to 2.5 microns) and improved signal/noise. It has 384 channels with the VNIR segment covering 0.4 to 1.0 microns in 5nm channels and the SWIR segment covering from 0.9 to 2.5 microns in 6.25 nm channels. The sensor operates in a pushbroom mode with 256 spatial channels. Although it is designed to operate up to 240 Hz frame rate, most operations will be between 15 and 60 Hz depending on altitude and aircraft velocity. The IFOV (or resolution) is 0.9 milliradians, which corresponds to a resolution of better than 1 meter from an altitude of 1000 meters. The total field of view is 230 milliradians. TRWIS III features outstanding MTF, spatial coregistration of spectral channels and cross track spectral performance. The 12-bit quantization provides very high dynamic range. The VNIR focal plane is a four ported, split frame transfer CCD with 768 spatial and 384 spectral detectors each 20 microns square. These are aggregated 3x3 to produce 256 spatial pixels by 128 spectral pixels. The SWIR focal plane is a Mercury Cadmium Telluride detector array with 60 micron square pixels. There is a 2.45 micron cutoff to reduce the effects of thermal noise. This cutoff, combined with fast optics and moderately long integration times at 60 Hz operation results in very good signal to noise characteristics as illustrated in Figures 5.

The HSI payload to be flown in the SSTI Lewis satellite is very similar to TRWIS III. In fact, one of the TRWIS III missions is to provide underflights for the satellite system during calibration and operations. The HSI system,(11) described in Table 1 and shown in Figure 6, is a compact 384 channel imager covering the spectral range from 0.4 to 2.5 microns. The sensor operates in a pushbroom mode with ground sample distance(GSD) of 30 meters and a swath width of 7.7 km. There is also a panchromatic focal array using the same optical system with a GSD of 5 meters and a swath width of 13 km. This will be used to evaluate the benefits of image sharpening for the hyperspectral image. The HSI instrument uses both solar and in-flight calibration sources and is predicted to have an absolute radiometric accuracy of better than 6%. The satellite system is designed for high accuracy pointing based on star trackers and GPS(12). During its first year of operation, the system is planned to take one image per day covering a ground area of 20 km x 7.7 km. Selection of image locations has been made based on demonstration objectives discussed below.

NASA Goddard Space Flight Center LEISA Payload

The Linear Etalon Imaging Spectral Array (LEISA) (see Figure 7) aboard the Lewis Spacecraft is a complementary imaging payload to the HSI system. It is a hyperspectral payload covering a spectral range from 1 to 2.5 microns in 256 channels. Underlying the concept is the use of a wedge type etalon with spatially dependent wavelength transmission placed in front of a two dimensional NICMOS 3 HgCdTe array to generate the hyperspectral images. The system is pointed to the earth by a mirror (optical pointing assembly) to allow off nadir viewing without turning the spacecraft. Based on a 77 km swath width, an image is designated as a 77 km x 77 km ground segment and up to 14 images can be acquired sequentially. The ground sample distance is 300m, or ten times larger than that of the HSI payload. With this and its broader swath, the instrument will address regional and global issues of earth resources, environment and disaster support.

Data Compression Archiving and Processing

Hyperspectral imaging data is typically formatted into cubes in which the base of the cube is a two-dimensional spatial image of the observed scene at a given wavelength and the height of the cube is built up of many 2-D image layers, each from a different spectral channel (see Figure 8). The resultant cubes are typically very large. The TRWIS B data cubes are either 14 or 28 MB. The HSI on Lewis will typically produce 120 MB or larger cubes. Thus, compression processing and archiving are pivotal issues in the effective utilization of hyperspectral data.

In order to make the most effective use of this new imagery and justify the cost of collecting it, we must find ways to make the information it contains more readily accessible to an ever broadening community of potential users. This will involve the development of tools and methods to store, access, and distribute the data more efficiently, to place it in context, and to derive both qualitative and quantitative information from it. Specifically it will require the generation from the same imagery of a variety of information products which address the specific needs of particular user communities.

A concept for an information system composed of a wide variety of geospatial data and based on a GIS is shown in Figure 9. Note that hyperspectral data is simply one type of imagery data in the system. Its unique capability is to supply detailed information about surface phenomena which are characterized by spectral signature of natural and man-made materials.

A hyperspectral data management and analysis system has been built at TRW. This development has been prompted by the business opportunities, by the series of instruments built here and by the availability of data from other instruments. The products of the processing system have been shown to prospective customers in the US and abroad. Figure 10 provides an overview of the TRW hyperspectral collection, data handling and exploitation capability. The Analysis and Exploitation functions deal with the digitized image cubes.

Digital data handling, analysis, compression and exploitation capabilities are implemented on standard Unix/C/X platforms including Sparc, Silicon Graphics and suitable data storage devices. The system and associated software are capable of handling AVIRIS, Landsat and other multiband data as well as data acquired by the TRW Imaging Spectrometers. All data display and processing is performed interactively using a set of image processing tools based on ENVI, a COTS package produced by Research Systems, Inc.

The system is shown in Figure 11. The input (Data Access) may be any multi- or hyperspectral data set. Since the entire data cube cannot be displayed, on-screen tools allow the analyst to select the bands to be used in the image displayed on the screen.

Much of our research in classification and compression has been incorporated into the system for continuous TRW internal development. Compression is needed to achieve more efficient transmission and receipt of data. It is very important that the compression technique preserve whatever information is essential for a particular user. A compression algorithm may preserve the spatial properties of the data while degrading the spectral; the converse is also possible. Thus, the performance of imagery compression algorithms needs to be related to the specific mission of the customer by developing suitable image quality measures.

The fine spectral resolution of the hyperspectral data typically results in high redundancy in the spectral dimension, so that hyperspectral datacubes are excellent candidates for compression. Both lossless and lossy algorithms have been implemented and tested. Compression ratios, in the case of the lossy implementations, exceed 50:1 with apparently acceptable quality in the spatial view of the imagery. Several papers have been published describing these techniques.(13, 14)

Four algorithms have been implemented for lossy compression of datacubes. Three represent extensions of wavelet-based algorithms developed earlier for single band imagery. The fourth is based on vector quantization and is especially useful for distribution of imagery over the Internet. The simplest approach treats the data as an ensemble of single band images and compresses each band independently, ignoring all correlations between the bands. This naive extension of the single band algorithm was used as a baseline against which to compare new algorithms optimized for the three dimensional data. However, it does have utility in cases where only a few bands will be reconstructed from the compressed data.

The spectral-decorrelation / wavelet coding(10) algorithm, as a second approach, uses a Karhuenen-Loeve transform (KLT) over the wavelength dimension to de-correlate spectral bands and applies a form of two-dimensional wavelet transform image coding to each band. Although this algorithm has outstanding rate-distortion performance, it is also computationally demanding. Computing the KLT requires many operations, and subsequent storage and manipulation of the transformed data requires extensive I / O and disk space.

The third approach directly generalizes the two dimensional transform coding by applying a three dimensional transform as part of the usual compression procedure. All three of the above approaches use discrete wavelet transforms.

For the fourth approach, TRW has implemented a vector-quantization based compression algorithm(15) . This technique offers great advantages for imagery to be distributed from an archive over the Internet. The compression process is highly asymmetric; compression is computationally intensive but decompression is very quick and can be easily done on a PC. Our goal is to have a suite of compression algorithms available so that users can select the techniques best suited to their applications. In general, our evaluation of the compression schemes will be based on a combination of statistical, visual and machine based descriptors. Once final processes are selected, they will be incorporated into archive and distribution system to support application research and development.

Applications Research and Demonstration Activities

One of the objectives of the SSTI Lewis program is to stimulate research and evaluation of space-based hyperspectral imagery. This includes the transition of research results into commercial products, a traditionally slow and sometimes random process. In support of this objective, TRW has assembled a broad team of university, commercial and educational organizations. These organizations address specific application foci generally grouped in the following way: natural and renewable resource evaluation, environmental analysis and planning. Partners have been paired so that there is a natural relation between a university, a commercial value-added reseller (VAR) and an end user. This encourages the transition of algorithms and analysis techniques into the market place.

TRW has 22 universities and schools on the Lewis Application Team. Agriculture, forestry and environmental studies are principal areas of investigation by the university researchers. In the case of agriculture, one of the primary objectives is to determine what soil and crop information can be obtained from remotely sensed hyperspectral data during the growing season. For instance, University of New Hampshire investigators will use satellite and corresponding ground data sets to test the capability of HSI to determine agricultural foliar chemistry and species identification. This complements their work with NASA and TRW under the SSTI program to examine canopy chemistry of selected eastern U.S. forests discussed in a following paragraph. Prairie View A&M University in Texas is studying the capability of HSI to observe chemically induced previsual stress in corn. This work will be done as a cooperative program with Purdue University. In another activity, Pacific Meridian, a VAR in California, is looking at crop typing and corresponding water utilization along the southern Colorado River near Blythe, California. In this study, images were made of an area near Blythe with TRWIS B mounted in the NASA Stennis Space Center Lear Jet and flown at 40,000 ft, giving a resolution of 1 2m and a swath width of 7 km. Extensive ground truth support was provided by a team led by Mary Balogh of the U.S. Bureau of Reclamation and staff of Pacific Meridian. An image from the flight is given in Figure 12. with selected crop identifications indicated. The identification was done with automated software after training the software by identifying a signature of each material type (see Figure 13). As might be anticipated, the success rate was 100% because sufficiently different plant types (alfalfa vs. melons) were being typed. Further studies with similar plant species are scheduled for the summer of 1996.

As with agriculture, there is substantial interest in forest canopy chemistry not only to address ecosystem phenomenology, but to improve efficiency in harvesting forests. Using AVIRIS, the University of New Hampshire team under Drs. John Aber and Mary Martin have been measuring the nitrogen and lignin levels in trees (private communication). This has led to a tree typing technique which appears capable of differentiating between subspecies such as red and white pine. In addition, results of hyperspectral measurements have been put into forest growth models which, when validated, will monitor the growth in wood stock on an annual basis (see Figure 14). During the next year, three forest areas, Harvard Forest in Massachusetts, a southeastern U.S. pine forest and a northwestern fir / spruce forest will be overflown to better understand the variability of results for different tree species and regional environments.

Approximately fifty percent of our university team members are carrying out studies in environmental and earth sciences. For example, the University of Colorado is developing algorithms using HSI data for spectral unmixing of complex landscapes to determine ecosystem process parameters. In this case, scene constituent basis vectors are used to evaluate pixels containing more than one plant type. Using both the lower resolution LEISA and the higher resolution HSI, the process of unmixing can be addressed through comparative observation for carefully selected test sites.

Another important area of research is the study of coastal zones, where traditional oceanographic techniques can be inadequate to examine critical aspects of coastal environments. Several University teams (e.g. the University of South Florida and Oregon State University) are attempting to use HSI for the development of hyperspectral algorithms and databases for coastal zones. Tidal zones involving estuarial flows and the impact of bottom conditions on localized hydrodynamics are specific subjects of investigation. This work nicely complements the wetland studies of Glenbrook Middle School and Contra Costa County Mosquito Vector and Control District in Concord, California in which wetlands are being actively reconditioned to bring back the tidal flows of fifty years ago.

As can be surmised from above, a lot of applications research is being planned in anticipation of the launch of the Lewis satellite in 1996. Preliminary airborne data is being used to initiate the research activities and it is hoped that in about a year, the first results using space-borne data will begin to emerge.

Conclusions

A new generation of hyperspectral imagers is being developed for space-based Earth remote sensing applications. Demonstration systems using grating and etalon dispersion will be flown during 1996 on the SSTI Lewis spacecraft being built by TRW. This system, and a matching TRWIS 3 airborne instrument, will be focused on Mission to Planet Earth research and on applications demonstrations for resource and environmental management.

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HYPERSPECTRAL IMAGING PAYLOAD FOR THE NASA SMALL SATELLITE TECHNOLOGY INITIATIVE PROGRAM

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Abstract

This paper describes the design and performance of the Hyperspectral Imager payload (HSI) currently being built for the NASA Small Satellite Technology Initiative (SSTI) program by TRW. The HSI is an earth observing, imaging spectrometer which combines two grating spectrometers and a panchromatic camera in one compact unit. The instrument produces images in 384 contiguous, uniform spectral bands between 0.4 µm and 2.5 µm. The hyperspectral images have 30 meter spatial resolution. A 5 meter panchromatic camera allows further spatial enhancement (sharpening) of the hyperspectral image. The optical system, focal planes and electronics are described. In-flight calibration features maintain radiometric accuracy of the instrument data, which is essential for the range of scientific, commercial and educational applications planned. HSI will fly on the "Lewis" spacecraft in 1996 and will be the first hyperspectral imager in space.

Introduction

Multi-spectral sensors are changing the way we look at the world. Space sensors currently flying are limited, however, to a handful of broad spectral bands on the order of 100 nanometers (nm) wide. Several aircraft instruments have been developed recently with approximately 10 nm resolution over the visible and short-wave infrared regions. The promise of improved science and commercial applications led NASA to include a High Resolution Imaging Spectrometer (HIRIS) in the early Earth Observing System (EOS) program. The dropping of HIRIS from the EOS manifest ended any public plans for a space based "hyperspectral" imager. The SSTI program provided an opportunity to field a technology demonstration of hyperspectral imaging from space, if significant obstacles could be overcome. The idea behind the SSTI program is to design, build and fly a small satellite which is a platform for advanced technology demonstrations.

The development challenges for hyperspectral imagers are daunting enough. The data rates and data volume for a hyperspectral imager are 2 to 3 orders of magnitude greater than multispectral imagers. The design, fabrication and testing for the Lewis Hyperspectral Imager (which will be referred to as simply "HSI" in this paper) had to be completed in 18 months to support the SSTI 24 months-to-launch program schedule. The small spacecraft bus used for Lewis placed further restrictions on instrument weight, power and volume. Our design for the Lewis HSI required the development of two new focal planes, new electronics and a new optical system [1]. We have overcome these challenges and will complete the instrument early next year (1996), with launch scheduled later that year.

The HSI will provide images with spatial resolution comparable to Landsat and Spot, but with 5 nm spectral resolution. The HSI payload is an experimental instrument and the spectral coverage and spatial resolutions were chosen to coincide with that of the Landsat and SPOT systems for data continuity and cross calibration. The HSI payload represents a leap forward in remote sensing because of its capability to perform spectral imaging. This capability holds many promises for the remote sensing community and therein lies the impetus to build and launch this type of instrument. What follows is a description of the HSI program, instrument and operation.

SSTI-HSI Program

TRW was awarded one of two contracts to design, build and operate a small spacecraft for NASA which demonstrated the SSTI program goals. These include advancing small satellite capabilities, reducing costs and development time, demonstrating new design/qualification methods, and promoting commercial applications from NASA/DoD technology. The "Lewis" spacecraft (named for the explorers Lewis and Clark by NASA), contains over 25 payload and spacecraft technology demonstrations. It is in part, a response to NASA’s "Faster, Better, Cheaper". In addition, the SSTI program promotes the formation of a broad coalition of commercial, educational and research organizations interested in the analysis of HSI data.

The satellite, to be launched from Vandenberg Air Force Base, will be placed in a 523 km circular, sun synchronous orbit (97° inclination). The spacecraft carries two other major instruments in addition to HSI. The Linear Etalon Imaging Spectral Array (LEISA) is a Short Wave Infrared (SWIR) imaging spectrometer which covers the 1.0 to 2.5 μm waveband. Its spatial resolution is one-tenth that of HSI and swath width is ten times as wide, which complements the HSI capability. LEISA has been combined with a pointing mirror to allow it greater line of sight flexibility. The Ultraviolet Cosmic Background (UCB) instrument is an extreme ultraviolet (55-105 nm) spectrometer designed for measurements of deep space. Together this suite of instruments will go along way to towards NASA's SSTI program objectives to demonstrate the utility of small satellites for both scientific and commercial endeavors.

HSI System Description

The HSI instrument is designed as a pushbroom scanner flying in a sun-synchronous polar orbit of 523 Km altitude. The instrument has three channels which share the foreoptics field of view, a panchromatic (PAN) channel, a Visible / Near Infrared (VNIR) channel, and a Shortwave Infrared (SWIR) channel. The ground track field of views of each channel are shown in Figure 1. The PAN channel includes a 1 x 2592 pixel charge coupled device (CCD) camera and 0.48 to 0.75 µm bandpass filter which, when combined with the 1.048 meter focal length F/8.3 telescope foreoptics, yields a 5 m ground sample distance (GSD) and 12.9 km swath width.

The VNIR and SWIR channels are separate grating spectrometers each of which images the spectra passing through an entrance slit at the image plane of the foreoptics onto a 2-dimensional focal plane array (FPA). The FPA dimension parallel to the slit provides for spatial sampling in the crosstrack dimension and the pixels perpendicular to the slit collect a spectral sample of each crosstrack spatial pixel. The effective size of each FPA is 256 pixels in the crosstrack dimension and 128 (VNIR) or 256 (SWIR) in the spectral dimension. The net result is that each frame samples the crosstrack line image spectra 384 times covering a wavelength range of 0.4 to 2.5 µm The along track motion of the spacecraft generates the second spatial dimension, providing an "image cube" 7.7 km in width, 384 spectra deep, and variable in length depending on the number of data frames taken.

Description of HSI Subsystems

The HSI Sensor Assembly (HSA), HSI Control Electronics (HCE), and HSI Power Electronics (HPE) are shown to scale in Figure 2. The HSA is mounted on the ram (forward) side of the spacecraft and the HCE and HPE boxes are mounted on internal panels.

An exploded view of the instrument is shown in Figure 3. The HSA contains the majority of the instrument functions and has several subassemblies including the optomechanical subsystem (OMS), three focal plane modules, three analog signal processor electronics boxes and aperture cover all contained in an enclosure assembly. The enclosure isolates and protects the OMS from the space environment.

The HSA enclosure consists of an outer enclosure temperature controlled to 293 K ±2 K which houses the OMS and provides the central structure for mounting the three analog signal processors (ASPs), FPA radiator, cryocooler and cryocooler radiator, aperture cover, solar calibration baffle, and in-flight calibration sources (IFCS's). The enclosure temperature is maintained at 293K by the instrument computer. As can be seen from the exploded view, the OMS supports a variety of other elements. The three FPA's are mounted on the OMS directly. Flexures at both the OMS and spacecraft interfaces prevent mechanical loads from distorting the optical system.

Separate radiators are required for temperature control of the focal planes. These radiators take advantage of the sun synchronous orbit and are mounted on the anti-sun side of the instrument. The SWIR focal plane is cooled to 115K by a pulse tube cryocooler and radiator. The VNIR and PAN focal planes reject their heat directly to a separate radiator on the side of the HSA. The cover assembly and calibration sources are mounted on the enclosure, as well as the ASP boxes for each focal plane. These boxes are thermally isolated from the enclosure and each include radiator surfaces.

The HCE electronics package processes digital video from the ASP boxes for reformatting and storage in an external data recorder, interfaces with the spacecraft via a 1553 interface bus and also processes the analog telemetry data. The HPE electronics provide secondary power from the spacecraft power bus and also contain heater, calibration source and cover motor drive circuits.

Optomechanical Subsystem

The HSI optomechanical subsystem collects the reflected sunlight from the ground and relays it to three focal planes. The OMS contains the optical elements and their support structure. It also provides mounting surfaces for the focal plane modules. The OMS combines an aluminum space frame with an aluminum optical system for a cost effective, lightweight design.

Foreoptics

The optical system has two distinct sections: the fore optics and the spectrometer. The foreoptics uses a 3 mirror off-axis design for the 12.5 cm aperture, one meter focal length assembly. The foreoptics layout, shown in Figure 4, has the spectrometer section mounted to the opposite side. The foreoptics consist of three powered elements, two fold mirrors, and a pick-off mirror which splits the field of view amongst the three instrument channels. The converging beam of the foreoptics is folded out of plane at the base of the Figure 4 and comes to focus in the spectrometer section, shown in Figure 5. The faceted mirror separates this converging beam into three different sections. The Panchromatic (PAN) camera uses a portion of the beam reflected downward off the faceted mirror. The VNIR and SWIR spectrometers use rays reflected upward to separate slits. These 3 parallel line images are separated in field by approximately 5 milliradians in object space. The PAN image is used directly, while the spectrometers relay the slit image through their optics to disperse it in the in-track (spectral) direction.

Spectrometers

The spectrometers, shown in Figure 5, use a common design with planar blazed gratings optimized for transmission in their wavelength range. The gratings are much coarser than normal owing to the wavelength range and 60 micron pixel size at the focal plane. The only refractive elements in the system are field lenses, placed just above the focal plane modules.

Temperature control of the HSA enclosure limits thermal gradients within the OMS structure, thereby maintaining imaging performance. The VNIR and SWIR spectrometers are housed along side of the foreoptics. Shear panels and blank offs prevent any stray light from entering the spectrometer housings except for that which passes through the entrance slit for each spectrometer. The three FPAs are mounted directly to the OMS with the PAN FPA located underneath the spectrometers and the VNIR and SWIR FPA's housed within their respective spectrometers.

Focal Plane Arrays

HSI Focal Plane Modules

The HSI instrument houses three focal plane arrays to cover each of the required spectral bands; VNIR, SWIR and Panchromatic. Each FPA is built up into an assembly level called the focal plane module (FPM). The FPMs are all required to provide a stable thermal, mechanical, optical and electrical platform for their respective FPAs.

Each FPA is thermally isolated from the OMS via a low conductance standoff. Thermal straps from the PAN and VNIR FPA to the FPA radiator provide for removal of resistive heating dissipated in each FPA and allow the VNIR FPA to be operated at approximately 273 K, significantly lowering dark current noise. The SWIR FPA is mounted on a sophisticated hexapod mount which provides extremely low thermal conductance while maintaining the structural integrity necessary for launch. The SWIR FPA is cooled to 115 K via conductance through a thermal strap to a TRW-built pulse tube cryocooler. A cold shield surrounds the field of view of the SWIR FPA to minimize thermal background.

The FPM's have a common mechanical mounting assembly which allows for positioning and shimming of each FPM to optically align the focal planes. Once aligned and locked down, the lower alignment assembly is removable. Each FPM also includes an electronic board assembly which provides for pre-amps, clock drivers and filtering adjacent to each focal plane, minimizing electrical noise. Each board has a pigtailed connector which connects to each FPM's respective Analog Signal Processor Box on the outside of the HSA.

VNIR CCD Array

The VNIR FPM is shown in Figure 6. The focal plane for the VNIR spectrometer is a custom silicon CCD. The CCD is a three phase device configured in a split frame transfer configuration. The basic pixel size is 20 microns with an active image area format of 768 x 384 pixels. The device has four output ports each of which readout one quadrant of the device. Upon readout the pixels are binned in 3 x 3 groups resulting in an image array of 256 x 128 binned 60 micron pixels. The arrangement in the VNIR spectrometer is 256 spatial pixels and 128 spectral pixels. The CCD is operated at 240 Hertz (Hz) frame rate resulting in a pixel rate of 2.4 MHz at each output port. The package housing the CCD is made of Kovar and configured to protect the device from radiation. The cover of the package also houses a spectral filter.

The electronics adjacent to the CCD provide four pre-amps, high speed clock drivers and various bias voltages. The electronics are thermally isolated from the OMS with the heat dissipated via the thermal strap.

SWIR MCT Hybrid FPA

The SWIR FPM is shown in Figure 7. The focal plane for the SWIR spectrometer is a custom Mercury Cadmium Telluride photodiode array and CMOS multiplexer hybrid. The array format is 256 x 256 pixels, each 60 microns square.

The SWIR FPA also operates at 240 Hz frame rate with four output ports running at 4 MHz each. Each pixel in the detector array is coupled to its own CTIA amplifier in the CMOS multiplexer and then coupled via switch FETs to one of the four output buffers built into the device. The hybrid is mounted onto a ceramic substrate which allows for bypass circuitry and fanout of the signal traces to the electrical cable which attaches to the SWIR ASP. The ceramic substrate sits on the package base plate and a cover, containing a spectral filter, mounts on top. Above the package is a cold shield which minimizes radiated thermal background by limiting the field of view to the detector array. Below, the package mounts to a thermal standoff assembly which thermally isolates the detector (at 115 K) from the optical bench (at 293K). The cooling is provided by an adjacent pulse tube cryocooler via the thermal strap. The remaining thermal path is through the electrical cable which is a lamination of kapton insulators and constantan/copper conductor layers which keep the thermal conductivity low.

Panchromatic CCD Array

The PAN focal plane array is a commercial CCD which has been re-packaged into a small ceramic flatpack package with a custom bandpass filter acting as a cover. The Pan FPM is shown in Figure 8. The device itself is a two phase linear CCD with 2592 pixels, each 10 microns square, and is read out through 2 output ports at roughly 2 MHz. The pixel size is 6 times smaller than the VNIR and SWIR pixels, hence the frame rate is run six times faster at 1440 Hz. The PAN FPM is similar to the VNIR FPM in that the module has the same mechanical alignment features, thermal strap and adjacent electronics for pre-amps etc.

Electronics Subsystem

Electronics Configuration

The bulk of HSI electronics are contained in five electric boxes, as shown in Figure 9, two of which are separate from the HSA and mounted elsewhere on the Lewis spacecraft. Each focal plane array is driven by its own analog signal processor box which is attached to the outside of the HSA. The combination of an FPM and corresponding ASP electronics is equivalent to a digital camera The digital video is collected, reformatted and passed onto a digital recorder by the HSI Control Electronics (HCE) which is under control from an embedded microprocessor. The secondary power and peripheral drive circuits are housed in the HSI Power Electronics (HPE) box which resides adjacent to the HCE on the spacecraft. Two key interfaces to the HCE are a 1553 command and control interface to an onboard processor and a 32 bit digital bus to the data recorder. Redundancy is provided in both the HCE and HPE by selection of the A or B side.

Analog Signal Processor Functions

Three ASP's, one for each instrument channel, are located on the anti-sun side of the instrument along with the FPA radiator to allow for maximum radiative cooling. Architecturally, each of the ASP boxes are the same in that they provide the each of the FPAs clock and bias signals and then process and digitize the returning analog video signals. The video data is digitized at 8-bits for PAN, 12-bits for VNIR and SWIR. Global offset is provided for each FPA from within the ASP, with global gain adjustment provided for PAN, global gain and integration time adjustment provided for SWIR.

HSI Control Electronics Function

The HCE is the central controller for the HSI instrument. Commands are sent to the HCE from the spacecraft computer via a 1553 interface. The HCE embedded microprocessor disseminates the commands to the aperture cover drive, calibration source drive, ASP's, and other internal functions. The HCE also provides the master clocking for the instrument and houses a pair of RAM buffers which store frames of PAN, VNIR, and SWIR data from the ASP's. The master clocking from the HCE synchronously pulses each ASP to control focal plane frame rate. The RAM buffers, operating in a "ping-pong" fashion, reformat the pixel data from the multiple FPA ports prior to sending the data to mass storage in the spacecraft's Solid State Recorder (SSR). Pixel data is sent from the HCE to the SSR via a 32-wire parallel interface operating at 16 Mhz.

HSI Power Electronics Function

The HPE's primary task is to provide secondary power to the HSA, HCE, all the ASP's and the peripheral drivers within the HPE. DC to DC converters are used to convert the spacecraft primary power (nominally 28 volts) to the various voltages required for all the units. Also included in the HPE are motor drivers to open and close the HSA aperture cover, current drivers for the In Flight Calibration Sources and some heater control circuits.

Calibration of Flight Hardware

The HSI calibration process will enable verification of sensor performance against what has been modeled. The predicted signal to noise performance is shown in Figure 10. There will be preflight calibration to verify the design performance which will then carry over to in flight calibration to maintain data integrity over instrument lifetime.

Pre-Flight Calibration

Performance is verified and radiometric calibration of HSI is performed during payload acceptance testing using the TRW Multispectral Test Bed (MSTB). The MSTB supplies a stable, uniform, spectrally variable source to the HSI instrument. This source is used for payload-level measurements including final alignment, monochromatic MTF, polarization sensitivity, signal to noise, linearity, dynamic range, spectral range, spectral band purity, spectral registration measurements, spectral calibration, and absolute radiometric calibration.

The HSI calibration approach is to absolutely calibrate the MSTB output in radiance, calibrate the HSI instrument spectrally as well as radiometrically by viewing the MSTB, then transfer the instrument calibration to the IFCS by viewing the in-flight sources. Spectral calibration of the MSTB is accomplished by inserting a HeNe laser in place of the lamp source and noting the monochromator settings at which the multiple HeNe orders pass through the system. Radiometric calibration is achieved by transferring radiometric power calibration from a NIST-traceable silicon trap detector at 633 nm to a spectrally-known pyroelectric detector covering the 0.4 to 2.5 μm wavelength range. The pyroelectric detector is subsequently installed in an all reflective telescope with calibrated entrance aperture, field of view, and spectral throughput. This telescope has approximately the same aperture as HSI. The telescope aperture and field of view are completely flooded by the MSTB source as are the HSI aperture and field of view, allowing for accurate calibration of MSTB radiance. The radiance is calibrated at bandwidths much greater than the HSI spectral resolution to spectrally flood all pixels.

On Orbit Instrument Calibration

On-orbit calibration is achieved by two overlapping approaches. The primary on-orbit calibration is performed using two In-Flight Calibration Sources (IFCS's). These two identical sources consist of a quartz tungsten halogen lamp, reflective optical element, and a baffle tube. Each lamp assembly illuminates the inside of the aperture cover which is painted with a diffuse white paint. The sources are designed to provide a broadband radiance at the HSI entrance aperture which is repeatable to 2% over the instrument life. The radiance is calibrated at three discrete set points during ground calibration.

Instrument calibration with the IFCS's is performed by taking a zero measurement with the cover closed and lamps off immediately before and after a given data collect. After the post-data collect zero has been taken, one lamp is powered on to two of the three set points for 30 seconds each. The highest set point includes powering the second lamp for an additional 30 seconds. Ten frames of calibration data are taken at the end of each 30 second period. Note that this calibration technique provides for repeatable calibration of the HSI instrument in radiance through the entire optical system.

The secondary on-orbit calibration approach uses solar illumination. Shortly after the spacecraft has come out of eclipse, when the spacecraft is directly above the terminator. sunlight passes through the solar calibration baffle mounted on the front surface of the enclosure. With the aperture cover partially opened, the sunlight will illuminate the diffuse white paint on the inside of the cover and will scatter into the instrument, flooding the aperture and field of view. The solar calibration baffle and interface to the aperture cover have been designed to prevent Earthshine or stray spacecraft glints from reaching the diffuser. The radiance of the solar diffuser will be measured early in the mission by HSI and compared to the IFCS to establish a second, highly repeatable source. In addition, the spectral reflectance and Bidirectional Reflectance Distribution Function (BRDF) of the diffuser will be measured prior to launch, allowing the solar calibration to be used as a second absolute radiance standard.

System Operation

The HSI operational concept is simple and straight forward. This is shown schematically in Figure 11. The instrument can perform a data collect at most once per orbit, a process which lasts less than 15 minutes of the 90 minute orbit. HSI tasking requests from the user community are submitted, approved and scheduled in advance by NASA Stennis. Ground position and approximate time of flyover are uploaded to the Lewis spacecraft and passed onto HSI in advance from TRW's operations center in Chantilly, Virginia. Few instrument configuration decisions are required. Desired spectral bands (any combination of the 384 bands plus the PAN) and swath length (up to the Solid State Recorder limit) are the primary decisions, with gain and integration time changes optional. The spacecraft computer then controls the sequence of updating the attitude required to align the HSI Line of Sight with the target, adjusting spacecraft attitude, configuring HSI properly and starting and stopping the imaging sequence.

The standard timeline for HSI imaging has the following steps:

1) switch to imaging mode from standby
    - power-up focal plane / ASP electronics, orient spacecraft pointing (10 minutes)
    - send x calibration frames to SSR at pre-target black level (< 1 second)
    - open cover (30 seconds)
    - start sending image data for selected bands, (time depends on bands selected, < 1 minute)
    - stop sending image data for selected bands
    - close cover (30 seconds)
    - send x calibration frames to SSR at post-target black level (< 1 second)
    - turn on calibration sources
    - take x frames of calibration data at 3 lamp levels (2 minutes)
2) switch back to stand-by mode

After HSI data is stored in the Solid State Recorder on board, a variety of data compression or further data manipulation is possible using the On Board Computer. Hardware and software data compression is available, but early data sets will likely be sent down untouched. Ground stations in both Chantilly, VA and Fairbanks, Alaska are available to receive Lewis data. Telemetry from HSI and the spacecraft must be merged with the image data to interpret where the instrument was pointing during an imaging pass. Calibration data taken before and after each pass may be evaluated to calculate current gain and offset corrections for each pass. Chantilly will forward the Level O data to Stennis Space Center for Level 1 processing and archiving.

Conclusion

We believe that the HSI instrument represents an significant advance in the field of remote sensing. This instrument will demonstrate the utility of hyperspectral imaging in both the scientific and commercial arenas. At the same time, the use of small inexpensive satellites to field sophisticated remote sensing instruments will also be demonstrated.

While advanced, the HSI capabilities are limited in both swath width and operational time. But with the data collected from HSI, the many advantages of hyperspectral imaging should be evident such that new and fully operational systems can become a reality.

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TRWIS III: AN AIRCRAFT-BASED HYPERSPECTRAL IMAGER

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Abstract

In recent years the utility of hyperspectral imagery for remote sensing and military applications has become increasingly apparent. Collecting images in hundreds of contiguous wavebands (channels) at a resolution of t to 10 nm provides a capability to discriminate and identify features of interest from the scene. Applications for hyperspectral imagery are continually being surfaced and include agricultural productivity, environmental monitoring and clean-up, geological surveying and mining, natural resource management, fishing, bathymetry, urban planning, and military target discrimination (e.g. mine detection, camouflage, identification friend or foe). TRW is developing an instrument with 384 contiguous spectral channels with bandwidths of 5 nm (Visible/Near Infrared) and 6.25 nm (Shortwave Infrared). The entire 384 spectral channels are simultaneously collected from each pixel in the scene. This instrument covers the wavelength range from 0.4 to 2.5 µm at signal to noise ratios of several hundred to 1 for a typical Earth scene. The instrument is calibrated at each wavelength to <5% absolute radiometric accuracy. It is designed to operate on various aircraft ranging from helicopters to Lear Jets, ultralights to unmanned aerial vehicles (UAV's). The design, fabrication, and testing of the TRWIS III instrument, which is approaching initial deployment, are described.

Introduction

Imagery from hyperspectral instruments with hundreds of contiguous spectral bands has demonstrated a powerful object discrimination capability. Early airborne instruments, including AVIRIS, TRWIS A, TRWIS B, TRWIS II, and HYDICE, have separated geologic features, foliage, and manmade targets from background when standard panchromatic and multispectral instruments could not. The high spectral resolution that hyperspectral instruments provide, typically in the 5 to 10 nm range, allows processors to search for targets with spectral features that are subtlety different from the background.

This powerful capability is important for remote sensing applications (e.g. geologic typing and surveying, agricultural monitoring and optimization, environmental damage assessment, forestry surveys, etc.) and for military applications (camouflage detection, identification friend or foe, target typing, mine detection, etc.).

The TRWIS III instrument is designed with two purposes, first as a research grade instrument capable of developing a high fidelity hyperspectral data base in the 400 to 2500 nm wavelength range and second as a first article in the development of production hyperspectral instruments. The top level performance requirements are for an instrument with extremely high signal to noise ratio (SNR), coregistered spectral channels taken simultaneously, GIS location knowledge, accurate radiometric calibration, and high quality imagery. Operationally the instrument is required to be multi-platform based and able to be flown on most aircraft.

Instrument development is nearly complete and preparations are underway for the first flight of TRWIS III. The instrument design and performance are presented below.

System Design

The TRWIS III instrument includes a sensor head containing a pair of co-boresighted grating spectrometers (see figure 1) and two electronics racks. The mechanical design of the spectrometers has been upgraded from the original version[1] to improve ruggedness, ease of alignment, packaging, and minimize temperature sensitivity. The Visible/Near Infrared (VNIR) spectrometer covers the wavelength range from approximately 400 nm to 1000 nm and the Shortwave Infrared (SWIR) spectrometer operates from approximately 900 nm to 2500 nm. Each spectrometer consists of a set of refractive foreoptics which image the scene onto a slit. Light passing through the slit is dispersed perpendicular to the slit by a flat grating and then imaged onto a two-dimensional focal plane array. One dimension of the array, the dimension along the slit, provides spatial scene information. The second dimension of the array, along which the light from any given point in the slit has been dispersed, provides spectral information. Pushbrooming the image of the slit across the scene perpendicular to the slit and storing subsequent frames of spatial/spectral information collected by the focal plane arrays (FPA's) generates a 2-dimensional spatial image with 384 spectral bands per pixel. These bands are 5 nm wide for the VNIR spectrometer and 6.25 nm wide for the SWIR. Instrument performance is summarized in Table 1. The predicted signal to noise vs. spectral channel shown in Figure 2.

A block diagram of the instrument is shown in Figure 3. Note that the instrument includes In-Fight Calibration Sources (IFCS) for both VNIR and SWIR spectrometers, on-board Global Positioning System (GPS), inertial sensors for pointing determination, electronics for instrument control, high speed data storage device, and a PC-based operating system. Each will be described in detail below.

The instrument is designed to interface with most aircraft. Early flights are planned this year in a Cessna 206 and in NASA Stennis Space Center’s Lear Jet. Interface requirements include mounting of the sensor head above a downward viewing window or port in the plane, mounting of the two standard electronics racks (one 24 in. tall, one 21 in. tall), providing 28 VDC power, and providing for GPS and FM broadcast band antennae mounting or connection. The variable frame rate of the instrument allows for flight plans from 600 m to 12 km in altitude and covering the flight envelopes of most aircraft in these altitude ranges (see Figure 4). The 0.9 mrad instantaneous field of view (IFOV) of the instrument results in spatial resolution ranging from 0.5 m to 11 m. The resulting cross track field of view (FOV) ranges from 128 m to 2.8 km over these altitude ranges with the intrack FOV limited only by the number of frames collected.

Opto-Mechanical Design

The two spectrometers are similar in optical configuration (see Figures 5 & 6). Both have multi-element refractive foreoptics which image the scene onto the entrance slit of the spectrometer. Light passing through the slit is reflected by an off-axis aspheric element onto a flat, blazed grating where it is dispersed. The reflected light from the grating is reflected by a second off-axis aspheric element and imaged onto the FPA. Refractive correction lenses are located two places, behind the slit and in front of the FPA, to minimize field distortion. If uncorrected this distortion would result in excessive spatial mis-registration of spectral channels and cross track spectral errors (also referred to as "smile"). An order sorting filter is located immediately above the surface of each FPA to eliminate order overlap.

The optics and FPA assemblies are mounted in custom mounts which provide for precision adjustment where required for proper alignment. Each mount is either pinned or staked with epoxy when alignment performance has been verified, resulting in a highly ruggedized assembly. The mounts are all attached to a common baseplate fabricated from Invar to minimize sensitivity to instrument temperature variations. An enclosure is attached to the baseplate to seal the optical system from the outside environment. All mounts and interior surfaces are painted black to minimize stray light effects.

The Analog Signal Processor (ASP) electronics from each FPA are mounted to the outside of the enclosure. For the SWIR spectrometer the compressor which provides for cooling the FPA is mounted to the outside of the baseplate. The inertial sensor is mounted to the VNIR baseplate within the spectrometer. Once assembled, aligned, and calibrated, the two spectrometers are attached with spacers between the baseplates and co-boresighted. The SWIR spectrometer foreoptics includes a minor zoom capability to allow matching of the VNIR and SWIR fields of view.

Table 1. Summary of TRWIS III Performance.

PARAMETER	PERFORMANCE
Weight (sensor head)	<39 Kg
Power @ 28 VDC	<800 Watts
Instantaneous FOV	0.9 mrad
Full FOV	13.1° (256 cross track pixels)
Number of Spectral Channels	384
Wavelength Range	400 to 2500 nm
Spectral Bandwidth	5 nm (VNIR), 6.25 nm (SWIR)
Spectral Band Purity	<24% adjacent channels, <3% 2 channels away, <2% 3 channels or farther
MTF @ 0.56 cycles / mrad (Nyquist)	>0.30 both cross track & dynamic in track
Cross track Spectral Error ("smile")	<1.0 nm (VNIR), <1.3 nm (SWIR)
Spatial Co-Registration of Spectral Channels	<20% of IFOV
Frame Rate	15, 30, or 60 Hz
Position Knowledge	<5 meters (when differential signal available)
Pointing Knowledge	<100 µrad roll, pitch, & yaw
Spectral Calibration Accuracy	<1.0 nm
Absolute Radiometric Accuracy	<5% (1 sigma)
Pixel-to-Pixel Relative Calibration	<2%
Quantization	12-bits
Data Storage Capacity	16 GB

Focal Plane Arrays

The focal plane module (FPM) for the VNIR spectrometer is a custom silicon CCD fabricated by Loral Fairchild Imaging Sensor (Tustin, CA) (see Figure 7). The CCD is a three phase device configured in a split frame transfer configuration. The split frame transfer minimizes smearing during the transfer process. The basic pixel size is 20 microns with an image area format of 768x384 pixels. The device has four output ports each of which readout one quadrant of the device. Upon readout the pixels are binned 3x3 resulting in an image array of 256x128 binned 60 micron pixels. The cover of the package houses an order sorting filter. An electronics board is mounted to the back of the CCD package and contains the preliminary amplifiers, high speed clock drivers and supplies the various bias voltages to the array. This board is attached to the VNIR ASP via an electrical cable.

The SWIR FPM is shown in Figure 8. The focal plane for the SWIR spectrometer is a custom Mercury Cadmium Telluride photodiode array and CMOS multiplexer hybrid fabricated by Rockwell International (Anaheim, CA). The array format is 256x256 pixels, each 60 microns square. The nominal operating temperature is 115 Kelvin. The array is mounted in a dewar and is cooled by a Stirling-cycle cooler.

Signals from the SWIR array are collected through 4 ports. Each pixel in the detector array is coupled to its own Capacitive Trans-Impedance Amplifier (CTIA) amplifier in the CMOS multiplexer and then coupled via switch FETs to one of the four output buffers built into the device. The hybrid is mounted onto a ceramic substrate which allows for bypass circuitry and fanout of the signal traces to the electrical cable which attaches to the SWIR ASP. The ceramic substrate is mounted to the end of the cold finger within the dewar. Immediately in front of the array is a field lens with an order sorting filter coating on the plano second surface of the lens. A cold shield which minimizes thermal background by limiting the field of view to the detector array surrounds the field lens and array surface.

Electronics

The TRWIS III electronics control both VNIR and SWIR cameras, record image and navigation data, provide a user interface for controlling the instrument and data flow, and regulate instrument power. Each camera is controlled by the TRWIS Control Electronics (TCE) which simultaneously clocks the two FPA's thru their respective Analog Signal Processor (ASP) units. The ASP's receive the analog pixel data from the FPA's, provide global gain, offset, and integration time adjustments to the SWIR FPA, and offset adjustment to the VNIR FPA, and digitize the data at 12-bit resolution. Once digitized the image data is transmitted to the TCE where a single frame from each camera is buffered. Buffering allows the data from each port of each camera to be organized before being sent to the high speed data recorder for storage. Buffering also provides for band selection, allowing any number of the 384 bands to be de-selected, thereby minimizing excess data.

Image data are written to the high speed data recorder through a PC-based frame grabber. On passing through the frame grabber two types of images are displayed in near-real time on monitors. One monitor contains the direct image of each focal plane array, with one monitor dimension spatial, the other spectral. This monitor is used to status the health of each FPA. A second monitor displays, in false color, the temporally sampled image of three selectable spectral bands for each spectrometer.

This monitor provides two (one VNIR, one SWIR), two dimensional, pseudo-color images of the scene. By watching this monitor the operator can verify scene features and assure that the proper images are collected during flight.

The instrument is commanded via a MIL-STD-1553B interface between the PC and the TCE microprocessor. This interface is used to set the SWIR gains, offsets, and integration time and the VNIR offsets on a port by port basis. It also sets the bands selected and starts and stops the flow of data from the instrument to the mass data storage. Temperature telemetry from the SWIR and VNIR focal plane array is recorded on the PC hard drive through this interface.

The high speed data recorder provides 16 gigabytes of memory. This allows storing approximately 80,000 frames of data with all spectral channels selected. This is equivalent to 22 minutes of data collection at the highest frame rate (60 Hz) or 88 minutes at the lowest frame rate (15 Hz). At 10 m resolution an area of more than 2000 Km^2 can be stored in a single flight. Upon filling the high speed recorder the data is downloaded to a Digital Linear Tape drive with 20 gigabyte removable tapes for archiving. The image data are merged and synchronized with the navigation data during the downloading process.

After downloading the data will be archived at TRW's Dominguez Hills data center. An automated software package is under development to process the data into image cubes with spatial dimensions 256 x 420 pixels and 384 spectral colors deep. The automated software will implement radiometric correction, geolocation and rectification, and image quality verification while converting the images to a format compatible with the ENVITM image processing software package produced by Research Systems, Inc. Distribution of the processed images will be via CD ROM with up to 6 image cubes per CD.

Navigation

The on-board navigation equipment includes the differential GPS receiver and inertial sensor. The GPS receiver supplies time and position data (Earth Centered Earth Fixed coordinates) to the PC where it is recorded on the hard drive. These data are updated at a 1 Hz rate and interpolated at a 60 Hz rate. A hardware flag from the GPS is inserted into the image data stream at 1 Hz to facilitate synchronization of the navigation data with the image. When differential signals are available, the combination of GPS and inertial sensor data provide position information at <10 m accuracy.

The inertial sensor provides pointing information about all three axes of rotation accurate to <100 μrad. The-signals from this sensor are synchronized with the frame sync supplied to the VNIR and SWIR cameras. This data is merged real-time with the GPS data and recorded in the navigation file on the PC. The resultant navigation file contains one block of data associated with each line in the image. Each block includes 6 axes of inertial sensor data (3 rotational velocity, 3 linear acceleration), a time tag, inertial sensor temperature (for drift compensation), and 3 position coordinates. Navigation data will be smoothed via a Kalman Filtering process during downloading to the digital linear tape archive.

Instrument Test & Calibration

The TRWIS III test and calibration process will enable verification of sensor performance against what has been modeled. Testing and calibration will be performed pre-flight with calibration updates during the flight provided by the IFCS. Pre-flight testing and calibration are performed using the TRW Multispectral Test Bed (MSTB) developed specifically for this purpose. The MSTB presents a stable, uniform, spectrally- and spatially-agile source of known spectral radiance to either of the TRWIS III spectrometers. This source is used for characterization and calibration measurements including final alignment, monochromatic MTF, polarization sensitivity, signal to noise, linearity, dynamic range, spectral range, spectral band purity, spectral registration measurements, spectral calibration, and absolute radiometric calibration.

The TRWIS III calibration approach is to absolutely calibrate the instrument in spectral radiance by viewing the MSTB, then immediately transfer the instrument calibration to the IFCS by viewing the in-flight sources. These two sources, one for the VNIR spectrometer and one for the SWIR, consist of a quartz tungsten halogen lamp mounted in a blackened, light-tight assembly. The assembly is mounted on a translation stage which is commanded to position the lamp at the entrance aperture for calibration. This allows the entire throughput of the optical system as well as the response of the FPA to be measured during in-flight calibration. The sources are designed to provide a broadband radiance at the TRWIS III entrance aperture which is repeatable to 2% over several months of instrument operation. With the lamp off the IFCS also provides a zero radiance reference to eliminate any errors due to drift in the instrument zero.

Instrument calibration with the IFCS is performed by taking a zero measurement with the IFCS immediately before and after a given flight line. In this mode the IFCS covers the instrument aperture and the IFCS lamps are off. After the post-data collect zero has been taken, each lamp is powered on to each of two set points for 30 seconds each. Ten frames of calibration data are taken at the end of each 30 second period. Note that this calibration technique provides for repeatable calibration of TRWIS III in radiance through the entire optical system.

Conclusion

High quality hyperspectral data is anticipated from the TRWIS III instrument. The accurate characterization and calibration planned and the excellent signal to noise expected for TRWIS III should further demonstrate the utility of this data in the 400 to 2500 nm spectral range. Data on most of the system components have been measured to date, including noise for both of the cameras through digitization, demonstrating that the instrument is meeting the predicted performance.

Several flights have been scheduled for the summer and fall of 1996. It is anticipated that new techniques and algorithms for processing the images will be developed with data from this instrument, further exploiting the discrimination power of hyperspectral imagery. Currently, real-time processing techniques are being investigated by TRW to support real-time target discrimination and minimize data storage requirements. The combination of high fidelity instrument performance and real-time processing is expected to be a significant improvement in target recognition capability.

References

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TECHNOLOGY CAN FORECAST VINEYARD DISEASE

Dan Clarke

In another era, growers shared information around the cracker barrel. While that willingness to share is a characteristic still found in today's farmers, the quality of their information is becoming much more valuable.

For the last two years, Napa County grape growers have had the advantage of access to portable, solar-powered weather stations. These stations, developed by **Adcon Telemetry**, forward information from the vineyard every 15 minutes via radio signals to a base station at the University of California Extension office in the city of Napa.

The weather stations can send their data via radio telemetry directly up to 12 miles or, if the distance to the base station is further, by using one or more other weather stations in relay. The units are lightweight and easily installed. Data logging and radio transfer are accomplished via five "C" cell batteries charged by a 4-inch by 6-inch solar panel. The solar panel, antenna and rain gauge are atop a pole about 15 feet tall, while the leaf moisture sensor protrudes from the pole and into the vine canopy. Additional sensors for soil moisture, soil temperature, wind speed and direction, solar radiation and air pressure are available. Cost of a sending station can range from just over $3,000 for the basic unit to $6-7,000 for one with additional sensors. Software necessary to access the base station is another $990.

Primary among the uses of these weather stations by Napa growers is early disease forecasting. Growers have 24 hour a day access to measurements of rainfall, humidity, temperature, leaf wetness, wind speed and direction and air pressure. They can call up the data and relevant risk assessment models on their computer screens with information as current as the conditions of 15 minutes prior. Naturally, growers are most concerned with the conditions in their own vineyards, but they can have access to data from other weather stations in the network, too.

Powdery mildew is a source of ongoing anxiety for Napa growers, particularly early in the season. Heretofore, the prudent grower sprayed on a regular calendar basis on the presumption that too much and too soon were preferable to too little, too late. However, several potential advantages occur if spraying applications can be extended; i.e., done less frequently over the course of a season. Cost of chemicals is reduced, as is cost of labor in applying them. Less unnecessary chemical is introduced to the vineyard environment and, also, more days of access to the vineyards are gained.

Dana Zaccone, vineyard technician for Domaine Chandon in Napa's Carneros region, says that the more precise information available to Chandon seems to be allowing for less frequent spray applications overall, allowing a cost saving. However, he notes that the model could predict a potential of mildew that might otherwise have gone unnoticed. In this case additional treatment cost would occur.

Growers have access to the data in an easily-interpreted form provided by the software package from Adcon and can schedule applications based on the software's risk assessment model. The Gubler-Thomas powdery mildew model was developed by Doug Gubler, Ph.D., from the Department of Plant Pathology at U.C., Davis and Carla Thomas, vice president agriculture for Adcon Telemetry. Traditional viticultural practice has been to apply sulfur or fungicide for the conidia stage of powdery mildew which occurs most rapidly between 70 and 85 degrees. A key aspect of the Gubler-Thomas model predicts vulnerability to the ascospore stage of powdery mildew which becomes a risk in spring when three conditions occur simultaneously: vineyard temperatures exceed 50 degrees, shoots have grown at least two inches and leaves are moist for more than 12 hours per day. It is believed that treating early incidence of the ascospore stage will minimize problems of conidia outbreak late in the season.

Chris Davidson manages 120 acres of vineyard land for Kirkland Cattle and Vineyards in Napa County's Jameson Canyon, adjacent to the Carneros. The first of her vineyards were planted in 1986 and the balance in 1995. Perhaps because of the relatively recent history of her plantings and their diversity (12 different varieties in all), Davidson is disinclined to take a "business as usual" approach. At present she has two Adcon weather stations; a basic unit in her original vineyards which she uses mainly for pest control and disease prediction and one with a wind meter for her new plantings which, being east of an irrigation field, have greater disease pressures because of the greater air moisture. Davidson's concerns are primarily for mildew and bunch rot pressures and comments, "when I spray it usually cost several thousand dollars so you want some reassurance that you're spending the money at the right time for the right reasons. I pay for my system the first time I eliminate one spraying.

"It's a needed, emerging tool. I think there will be expanding uses and those who don't accept this kind of technology will be guessing. A winery is more comfortable buying from a grower who has a better grasp of their disease problems—and is not just guessing." Flexibility may be a key in utilizing this technology. Don Luvisi University of California Extension Farm Advisor for Kern County, reports 13 sending units in his county, five south of Bakersfield and eight to the north. "I'm happy with the information and the equipment," he says, "once I have confidence in the disease model and it says stretch my applications, I can do it. But I'm working with large growers—probably none less than 1,000 acres and all equipment is scheduled." To this point, adapting schedules for equipment and labor has proven a sticking point and Luvisi has not seen the program's potential realized in his county.

While growers are most concerned with their own vineyards, information from any weather station is available to all participating in the network. Paul Kenney, who manages northern Napa Valley vineyards for Sterling, has weather stations on his properties in the Calistoga area but appreciates the access to everybody else's information. Kenney says that the main reason for purchasing an Adcon system was for disease forecasting. While it did allow him to stretch his sulfur applications somewhat during the ‘95 season with a consequent saving, the ‘96 season has been so hot that powdery mildew has not been much of an issue. However, Kenney believes the long-term temperature tracking is an equally valuable aspect of the system. “Before, we had these old, wind-up thermographs which were hard to calibrate,” he says. “These systems are so much simpler. Especially because the hills here are all so different, long-term record collecting is important. You can see what temperatures were like over a five-to ten-year period and can tell what varieties would do well in any vineyards you might acquire or develop that are similarly situated.”

Though the original programs were established in Napa, Sonoma and Kern counties, other networks are now expanding throughout California.

Overall, this technology has allowed most growers to produce healthier crops with fewer pesticides at a lower production cost. Observing this success in the grape industry, Western Farm Service is establishing a 450 weather station network in California which will service a variety of crops. Among these will be grapes, strawberries, citrus, tomatoes, potatoes, carrots, avocados, cotton, wheat and corn. Growers can purchase their own weather stations which are connected to these base stations and have computer access on a 24 hour basis or have the base stations fax information to them on a regular schedule. Western Farm projects they will have weather stations operating in 85% of California’s major agricultural areas by the end of 1996 and are establishing similar network in Oregon, Washington and Idaho.

Though powdery mildew may be of the greatest concern to Napa and Sonoma grape growers, various other diseases and insects pose peril to other crops. The AgroExpert software that comes with the weather stations addresses these. It can calculate degree-day values which are useful in crop growth, yield and harvest estimates, as well as insect management. Degree-day values also are important in determining when to release predatory or beneficial insects, allowing growers to use fewer insecticides. Wind speed sensors alert the grower when it is too windy to spray pesticides safely. Growers can use the same weather stations to schedule irrigations by calculating evapotranspiration values and by measuring soil moisture. With this tool, growers can reduce ground water contamination, conserve water usage and manipulate harvest dates and crop yields better. While participating farmers may not yet be able to change the weather, they are acquiring some tools to help them better decide how they will respond to it.

Further information about this technology can be obtained by calling Adcon Telemetry at (1) 800-352-5309 or accessing their web site at http://www.adcon.com/

AIRBORNE IMAGING AIDS VINEYARD CANOPY EVALUATION

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During the 1993 and 1994 growing seasons, airborne digital sensors were used to collect visible and near-infrared images of phylloxera-infested vineyards near Oakville in Napa County. Computerized processing enhanced the information content of the images with respect to leaf area of the canopy. Processed image values were strongly related to ground measurements of vine pruning weight and leaf area made within a 12-acre study site. The images were useful for mapping patterns of leaf area throughout the site and in surrounding vineyards, and for assessing year-to-year changes in canopy. The vineyard manager found the imagery valuable in planning for replacement of phylloxera-infested fields, managing for crop uniformity and segregating grapes of differing quality during harvest. This tool was particularly useful in evaluating and managing newly acquired property.

Many grape growers routinely use interpretation of color-infrared aerial photographs as a vineyard monitoring tool. The aerial view reveals growth patterns that may not be obvious from ground level, helping growers to locate and more effectively manage problem areas and to assess year-to-year changes in management practices.

Investigators at NASA / Ames Research Center in Mountain View, in collaboration with UC Davis, UC Cooperative Extension, California State University at Chico and the Robert Mondavi Winery in Oakville, (Napa County) recently evaluated the use of digital image processing techniques for vineyard assessment. Images collected over the Napa Valley were processed to enhance and map spatial patterns and show year-to-year differences in vineyard canopy size.

As the name implies, the Grapevine Remote-sensing Analysis of Phylloxera Early Stress (GRAPES) project was initiated in response to the grape phylloxera (*Daktulosphaira vitifoliae* [Fitch]) infestation, which affects a number of California grape-growing regions and is pronounced in the North Coast (*California Agriculture* March-April 1991). The insect (Biotype B) is a form of plant lice that debilitates the root system, depriving the vine of water and nutrients and posing increased management problems in the form of reduced vine growth, decreased grape yield, retarded grape maturation and lower wine quality. Phylloxera outbreaks tend to appear in satellite locations, adding to management time and cost. The infestation spreads rapidly through the vineyard and vines typically succumb within 3 to 5 years of initial infestation.

Pesticide application is not effective for phylloxera control, due to the deep rooting of grapevines and to the high rate of phylloxera reproduction. No effective biological control agent is known. Management practices (more severe pruning, additional irrigation and fertilization) may lessen phylloxera impact for the short term, but the only long-term solution is to remove the infested vines and replant with a more resistant rootstock. Improved knowledge of the current and potential future extent of phylloxera infestation would enable growers to make better-informed decisions for nearterm management and for replanting. The GRAPES project builds on the earlier work of Wildman et al. (1983, *Am. J. Enology and Viticulture* 34(2):83-94), who used color-infrared photography to monitor phylloxera damage and estimate spread rate.

For aerial observation, the most pronounced symptom of phylloxera-induced stress is decreased vegetative growth. Because canopy reduction is a common stress indicator in perennial and annual crops, we believe that the analysis presented here is relevant to the broader agricultural community.

Measurements & Manipulations

Shortly before the 1993 growing season (early May), a partially infested field of Cabernet Sauvignon vines grafted to AxR#1 rootstock was chosen as the study site. Mondavi’s 12-acre vineyard near Oakville was planted in 1981 in Clear Lake clay and Bale clay loam soils. The vines were trained on a standard two-wire trellis without shoot positioning. Rows were 12 feet apart, oriented northeast to southwest; within-row vine spacing was 8 feet. The site was clean cultivated with hoe plows and discs.

Nine study plots were established in the study site (fig. 1), each plot consisting of a total of 40 vines (4 rows, 10 vines per row). The plots were delimited on the basis of grower knowledge, a 1992 aerial infrared photograph and a phylloxera survey involving excavation of shallow roots and visual examination of phylloxera population through a hand lens (table 1). Plots 1 through 3 were visually symptomatic, with obvious reductions in shoot length and leaf area and some vines with visible leaf chlorosis. Plots 4 through 6 were infested but visually asymptomatic, and plots 7 through 9 were uninfested. The phylloxera survey showed mean ratings, based on a subsample of nine vines per plot, of 1.5 (plots 1-3), 0.5 (plots 4-6) and 0.0 (plots 7-9). Two Global Positioning System (GPS) receivers were used to determine latitude/longitude coordinates for the study site and plot boundaries. The commercially available receivers computed location by receipt of radio signals from the GPS satellite network, maintained for military and civilian use by the U.S. Air Force.

	TABLE 1. Criteria for phylloxera rating
Rating	Observation
0	No phylloxera found
1	Phylloxera only on rootlets, or one or two individuals on older (than one year) roots
2	Individual phylloxera scattered among older roots, or one or two colonies on older roots
3	Several colonies established on older roots
4	Large populations of phylloxera present on older roots

Vine-leaf area was measured by sampling 14 vines per plot in mid-July and mid-August 1993. The number of shoots on each sampled vine was recorded, then all leaves with widths greater than 0.5 inch were removed from two randomly selected shoots per vine, placed into polyethylene bags and stored in an ice chest. The surface area of each leaf was measured in the laboratory with a LI-COR Model 3100 (Lincoln NE) leaf area meter within 36 hours of collection. Means for per-vine leaf area (ft^2) were 57.1 (plots 1-3), 95.0 (plots 4-6) and 91.7 (plots 7-9). Leaf area measurements were not made in 1994. (To a large extent, plots 4-6 were visually asymptomatic in mid-1993. The small difference between leaf area in plots 4-6 and plots 7-9 was not statistically significant.)

Canopy size was affected by management practice throughout the study site in 1993 and 1994. In addition to normal spring removal of suckers, the grower balanced the crop-to-leaf ratio by removing shoots and grape clusters in early July 1993, which resulted in a canopy reduction. During the following dormant season, the grower pruned to a lower bud count throughout the site. The intention was to decrease the number of shoots in 1994 relative to 1993, yet increase shoot length and leaf area per shoot. Midseason shoot removal was not performed in 1994, due to a satisfactory balance between shoots and grape clusters.

In the dormant periods following the 1993 and 1994 growing seasons, pruning weights were obtained for each of the 40 vines in each plot. The pruning weight is the total weight (pounds) of shoots per vine, less a small amount of shoot growth retained to support the following season's growth. Mean per-vine pruning weight in each plot for 1993 was related to mean per-vine leaf area as: leaf_area = 49.1 + 8.0*prun_wt, $r^2 = 0.58$, $n = 9$. We used the mean pruning weight per vine in each plot (fig. 2) to assess differences in canopy size among plots within season, and also per plot differences between 1993 and 1994. Infested plots 14 showed year-to-year declines in pruning weight, presumably associated with continued phylloxera-induced stress. Plots 7-9, which were uninfested or lightly infested, had greater pruning weights in 1994 than in 1993, we believe as a result of the more aggressive pruning. Pruning weights were negatively correlated with midseason phylloxera ratings in both 1993 (prun_wt = 5.8 1.5*p_rating, $r^2 = 0.71$, $n = 9$) and 1994 (prun_wt - 8.4 - 3.5*p_rating, $r^2 = 0.72$, $n = 9$), suggesting that phylloxera stress influenced canopy size in the study site.

Reconciling Different Images

Digital sensors were used to collect images over the Napa Valley and vicinity during the 1993 and 1994 growing seasons. The images were recorded as a matrix of numbers on a computer disk rather than on film, each number representing the brightness of each picture element, or "pixel" (minimum resolvable area on the ground). The digital images were computer processed to enhance information content, and were visually examined either on a computer screen or as paper prints.

The Compact Airborne Spectrographic Imager, a commercial scanner developed by ITRES Research (Alberta, Canada), flew at 4,000 feet aboard a light aircraft to collect images over approximately 5,000 acres of vineyard near Oakville on July 28, 1993. The images measured light reflected from the vineyard in the blue, green, red and near-infrared spectral regions. The pixel resolution of the imagery was 6 feet by 6 feet. Two weeks later, film-based color-infrared photographs were collected at scales of 1:6,000 inches and 1:32,000 inches by NASA aircraft.

The GRAPES project was designed in part to evaluate the use of image processing techniques to reconcile images from different sensors having somewhat different imaging characteristics, a situation that might be encountered in practical operation. Therefore a different sensor was flown in 1994: an electro-optic camera, developed and operated by NASA / Ames Research Center. The camera acquired imagery in the green, red and nearinfrared regions over a large portion of the Napa Valley and adjoining Carneros region on August 1. Approximately 40,000 acres were imaged in 1 hour near midday by a NASA ER-2 aircraft flying at 65,000 feet. The images had a pixel resolution of 15 feet by 15 feet. At the same time, the ER-2 collected film-based color-infrared photographs at a scale of 1:32,000.

Color-infrared images of 12-acre study site acquired by airborne digital sensors on July 28 1993 (a) and August 1, 1994 (b). High leaf area shown as red; lower leaf area tends toward blue-gray. Images were computer enhanced to improve contrast. Locations of the nine study plots are superimposed.

Using image-processing software, the 1993 and 1994 images of an approximately 700-acre parcel including the study site and surrounding area were "ground registered" (a map coordinate was assigned to each imag pixel) using a translation based on the GPS map coordinates. The GPS coordinates were also used to delineate the nine study plots in the imagery. The 1993 pixel resolution (6 feet) was degraded to match that of the 1994 scene (15 feet). The software was then used to generate a color-infrared picture from the data, and a contrast enhancement was applied to accentuate canopy patterns within the site (see images a and b above).

Normalized Differences

Various combinations of nearinfrared and red reflectance have been shown to be sensitive to the amount of photosynthetically active vegetation present in the plant canopy (Tucker, 1979, Remote Sensing of Environment 8:127-150). Reflectance of near-infrared light from plant canopies tends to be positively correlated with the amount of leaf surface area per unit ground area, while reflectance of red light tends to be negatively correlated with leaf area. For this analysis, a normalized difference vegetation index (NDVI) image was generated for both years by calculating for each pixel the quantity.

NDVI = (NIR - RED) / (NIR + RED) where NIR and RED are light recorded by the sensors in near-infrared and red frequencies. In addition to leaf area sensitivity, the NDVI tends to lessen the influence of brightness differences associated with solar illumination or sensor viewing angle. In an earlier study (Pearson et al., 1994, *Remote Sensing of Environment* 49:304-310), NDVI imagery was used to detect stress in a number of high-value annual crops in Wisconsin.

The NDVI generally ranges from near 0.0 for bare soil to near 1.0 for dense canopy. Due to the relatively large proportion of exposed soil found in the study site (typical of vineyards), the mean NDVI for the study plots occupied the low end of this range: 0.190.38 in 1993 and 0.13-0.37 in 1994. The 1993 mean NDVI per plot was related to field measurements of leaf area as: NDVI= -0.75 + .56*LOG(leaf_area), $r^2 = 0.79$, n = 9. For the combined 1993 and 1994 data set, the mean NDVI per plot was related to mean per-vine pruning weight as: NDVI = 0.15 + 0.24*LOG(prun_wt), $r^2 = 0.72$, n = 18.

The absolute value of the NDVI may be affected by factors unrelated to changes in the crop canopy (for example, year-to-year differences in atmosphere, sensor response). To lessen this influence, an image processing routine was used to assign each NDVI pixel to one of 12 levels ranging from low to high NDVI. These relative NDVIs were color coded to facilitate visual discrimination, with brown corresponding to the lowest NDVI level (1), dark green corresponding to the highest NDVI level (12) and black (0) corresponding to areas of no apparent vegetation (images a and b above). For the combined 1993 and 1994 data set, the relationship of mean relative NDVI to mean per-vine pruning weight (fig. 3) was somewhat stronger ($r^2 = 0.76$) and more linear than that observed with absolute NDVI.

To show year-to-year changes in canopy, the 1994 relative NDVI image was digitally superimposed upon and subtracted pixel by pixel from the 1993 image (see image p. 18). Consistent with the pruning weights, the resulting image shows a decline in canopy at and near plots 1-6, due mostly to phylloxera infestation, and constant values or year-to-year increases at and near less infested and uninfested plots 7-9.

Practical Evaluation

Color-infrared and relative NDVI images were provided to the grower both as paper prints and as digital files compatible with the grower's geographic information system software (ArcView 1.0; Environmental Systems Research Institute, Redlands). Using this software on a laptop computer, the grower was able to enlarge, view and print the images. The images were shared with various company personnel, who generally felt that it agreed with their perception of the property. The imagery provided an objective measure of canopy cover that corroborated field observations and measurements. The consensus was that the relative NDVI images (above) were far easier to interpret visually than either the contrast-enhanced color-infrared images (such as the images on p. 16) or film-based color-infrared photographs, which were believed to be about equal in information content.

The imagery, essentially a map of strong and weak areas throughout the vineyard, was used to target areas for investigation and possible remedial action to improve vineyard uniformity. Field verification showed that canopy differences observed in the images were generally related to either phylloxera infestation or soil waterholding capacity. Considered along with other routine measurements and observations, the imagery was useful for evaluating the viability of particular fields with regard to phylloxera stress (as judged by canopy size and uniformity) and in making replanting decisions during the study period. The images were used to place backhoe pits for soil investigation prior to replanting, resulting in establishment of new block boundaries that more closely match soil patterns and thus should simplify management and enhance crop uniformity. This tool was found to be particularly useful on newly acquired property, with which management was less familiar. The imagery was also used for strategic placement of sampling sites to monitor brix, and we feel is potentially useful for establishing sample sites for node levels and cluster numbers for improved yield prediction.

Maturity measures (Brix, titratable acidity, pH and taste) were different between the strong and weak areas shown in the imagery. In a limited test, the imagery was used to subdivide fields for harvest based on observed patterns of strength and weakness. Resulting wine quality was found to be dramatically different between the strong and weak areas; strong areas were of "Reserve" quality, weak areas were of lower quality. Thus, where uniformity cannot be improved, the imagery will help to prevent the combining of differing quality harvest into the same wine lot.

The imagery provided a direct comparison of the current and previous season’s canopy (such as the image above). With this, the grower was able to assess the rate of phylloxera spread (by vine and block) and to project its future extent, again in support of replanting decisions. Year-to-year comparison was also useful for assessing the effect of pruning and other management practices on canopy size and uniformity.

Availability of the Technology

In the GRAPES project, airborne digital sensors acquired imagery over increasingly large regions during each year of the project. In 1993, coverage was limited to the Oakville vicinity in the Napa Valley. In 1994, coverage included most of the Napa Valley and the Carneros region (southwest of the city of Napa). In 1995, the project acquired imagery over much of the vineyard region in Napa and Sonoma counties. Since 1995, at least one commercial service in California collects and processes digital imagery over agricultural lands, delivering colorinfrared images on paper or computer media to clients within 48 hours of overflight. These images are suitable for subsequent processing into absolute and relative NDVI products. Beginning in 1998, planned commercial satellite systems will acquire visible and near-infrared imagery with sufficient pixel resolution (about 15 feet) to be of use in agricultural management. The image processing steps outlined here are within the capabilities of commercial remote sensing and geographic information system vendors, and perhaps could be incorporated at the level of the agricultural consultant.

Currently and for the near future, the most common way to generate a digital image is to scan a color-infrared aerial photograph. In GRAPES, a common desktop scanner was used to convert 1993 and 1994 film products of the study site to digital format. Limited in vestigation produced relative NDVI results similar to those reported here for the digital sensors. One disadvantage of this approach is slower turn-around time due to film processing, which may prove unacceptable for some agricultural applications that require quick response. Finally, trends in technology are combining to enable the manipulation of processed imagery and other spatial data at the grower or grower-consultant level. These include dramatic improvements in the cost/performance of personal computers and image display / geographic information system software, and the continued evolution of commercial GPS receivers to permit accurate and rapid collection of geographic data for coupling fieldwork with imagery.

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Additional information on the GRAPES project is available on the World Wide Web at http://geo.arc.nasa.gov/sge/grapes/grapes.html

Other links: http://geo.arc.nasa.gov/sge/crush/crush.html

Interested parties are welcome to contact Johnson regarding the availability of image data sets for Napa and Sonoma counties.